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Opportunities in Applied Physics

FOR the past several years physical science has been advancing at a record-breaking pace. In certain quarters, this progress has aroused a fear that society will suffer unless in some way these advances can be readily assimilated by the younger and less well-developed social sciences.

In many respects, the relation between physics and these other sciences may be visualized if one considers all knowledge as a large sphere with a dense interlocked and well-substantiated body of fundamental natural laws at the center. Outside of this center, a sparser region occurs where laws have a somewhat more empirical basis such as those in engineering and in the biological sciences. Beyond these are the social sciences, and still further in the rather nebulous outer regions, are the arts which as yet have no scientific basis.

At one time it was thought that the inner sphere representing the fundamental laws of physics was fixed in size so that, after a few gaps had been filled, it would be complete and then physicists would necessarily devote their energies to other fields. Time has shown, however, that as physicists penetrate deeper into the laws of nature, the outer surface of the sphere expands. Fortunately, although this deeper insight has changed entirely our ideas of the behavior of particles of extremely small mass, most of the outer regions representing the classical laws and concerned in the main with bodies of large mass remain essentially unchanged except that the range of application increases at an ever growing rate.

If, then, alarm is raised by the growing number of gaps in this structure lying just beyond the fundamental laws of nature, is not this a proper place for greater activity? If knowledge in the less well-developed sciences is to be placed upon a firm basis, surely it is necessary to fill in not only the old gaps between classical physics and engineering and the biological sciences, but also those gaps arising out of recent developments in subatomic physics. Thus, as time goes on, the field of opportunity for those working in borderline fields is continually widening, and the future is indeed bright for applied physics.

—THE EDITOR

For June

What Electrons Can Tell Us About Metals, by C. J. DAVISSON

The Dynamics of a Bow and Arrow, by C. N. HICKMAN

Electronic Structure of Alloys, by J. C. SLATER

Alloys for Tools and Wear Resistance, by ZAY JEFFRIES

Electrochemical Techniques in Corrosion Study, by R. M. BURNS

Contributed Research Papers on Double Refraction in Colloidal Solutions, A Problem in Potential Theory, The Wetting of Filaments by Molten Metals and The Creep of Solids at an Elevated Temperature.

The National Bureau of Standards

By LYMAN J. BRIGGS

THE National Bureau of Standards has its origin in that provision in the Constitution which delegates to Congress the power to "fix the Standard of Weights and Measures." For more than 40 years Congress took no action under this delegated authority although the subject of weights and measures was frequently under discussion—a discussion which included the consideration both of the metric system and of a unit of length based upon the length of a seconds pendulum. In 1830 the Senate instructed the Treasury Department to investigate the weights and measures used in the several customs houses with a view to bringing about uniformity. The outcome was the adoption by the Treasury Department without further action by Congress of certain standards of weights and measures that accorded as closely as circumstances would permit with those already in use. Congress then authorized a distribution of replicas of these standards to the various States. The construction of these standards was carried out by the Coast and Geodetic Survey, a branch of the Treasury Department, and its office of weights and measures continued as the custodian of the national standards until the establishment of the National Bureau of Standards in 1901.[1]

SAMUEL W. STRATTON, *Director*, 1901–1922.

The standards of length, mass, and capacity, thus set up have since come to be known as our "customary" system of weights and measures, which differs in some of its units (notably the gallon and bushel) from the present system in use in Great Britain. In 1866 the use of the metric system was legalized by Act of Congress, and sets of metric standards were distributed to the State governments to supplement those distributed 30 years earlier. As in the case of the earlier standards, these included standards of length, mass, and capacity only. During the latter part of the nineteenth century the need for uniformity in the "derived standards" became more and more acute. The development of the electrical industry, in particular, brought this matter to the front, for it was necessary for manufacturers and users of electrical instruments to send these devices abroad for comparison with a recognized standard. This led to the recommendation by the Electrical Congress which met in Philadelphia in 1884 that a National Bureau of Physical Standards be established in the United States. The proposal was later strongly supported by leading American physicists, notably by Rowland, Webster and Michelson. Still, the one man needed to bring about some definite accomplishment was lacking. At the very close of the century he appeared in the person of Dr. S. W. Stratton, professor of physics at the University of Chicago. With a full appreciation of the need of exact standards in science and industry, he succeeded in interesting the then Secretary of the Treasury, Honorable Lyman J. Gage, and numerous members of Congress in his plans for a national bureau which would have custody of all classes of standards.

In 1899 Dr. Stratton was appointed chief of the Office of Standard Weights and Measures, where he had the able assistance of Dr. F. A. Wolff and Louis A. Fischer. Working with Secretary Gage, and supported by the leading scientists and

[1] For an interesting summary of the early history of weights and measures in this country, see Sarah Ann Jones, *Weights and Measures in Congress* (Misc. M122, National Bureau of Standards, 1936).

engineers of the country, their efforts culminated in the passage of a bill by the Congress on March 3, 1901, creating the National Bureau of Standards.

Functions

The original organic act establishing the Bureau reads in part as follows:

". . . the functions of the bureau shall consist in the custody of the standards; the comparison of the standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the Government; the construction, when necessary, of standards, their multiples and subdivisions; the testing and calibration of standard measuring apparatus; the solution of problems which arise in connection with standards; the determination of physical constants and the properties of materials, when such data are of great importance to scientific or manufacturing interests and are not to be obtained of sufficient accuracy elsewhere."

". . . the bureau shall exercise its functions for the Government of the United States; for any State or municipal government within the United States; or for any scientific society, educational institution, firm, corporation, or individual within the United States engaged in manufacturing or other pursuits requiring the use of standards or standard measuring instruments. All requests for the services of the bureau shall be made in accordance with the rules and regulations herein established."

It will be observed that nothing is said about external regulatory or police power, and, as a matter of fact, the Bureau exercises no power of this kind. It is, however, called upon extensively for consultation and technical advice by many Government agencies and this service, together with the preparation of Federal specifications and a voluminous mail on every conceivable question within the scope of its activities, now requires 15 percent of the time of the entire technical staff. The Bureau is also the largest laboratory maintained by the Government for testing of supplies purchased on specification. This is a service function that probably was not foreseen in earlier days, as no reference is made in the organic act to the testing of materials or supplies for the Government. Yet at the present time more than half of the technical staff of the Bureau is engaged in this work. The development of this activity was inevitable under the present system of Government purchases. Supplies are purchased through open competitive bidding with the stipulation that the material purchased must meet the requirements of some particular Government specification. This involves an enormous amount of detailed laboratory measurement at the Bureau, despite the fact that foodstuffs and military and naval supplies are examined in other laboratories.

GEORGE K. BURGESS, *Director*, 1923–1932.

LYMAN J. BRIGGS, *Director*, 1933 to the present time.

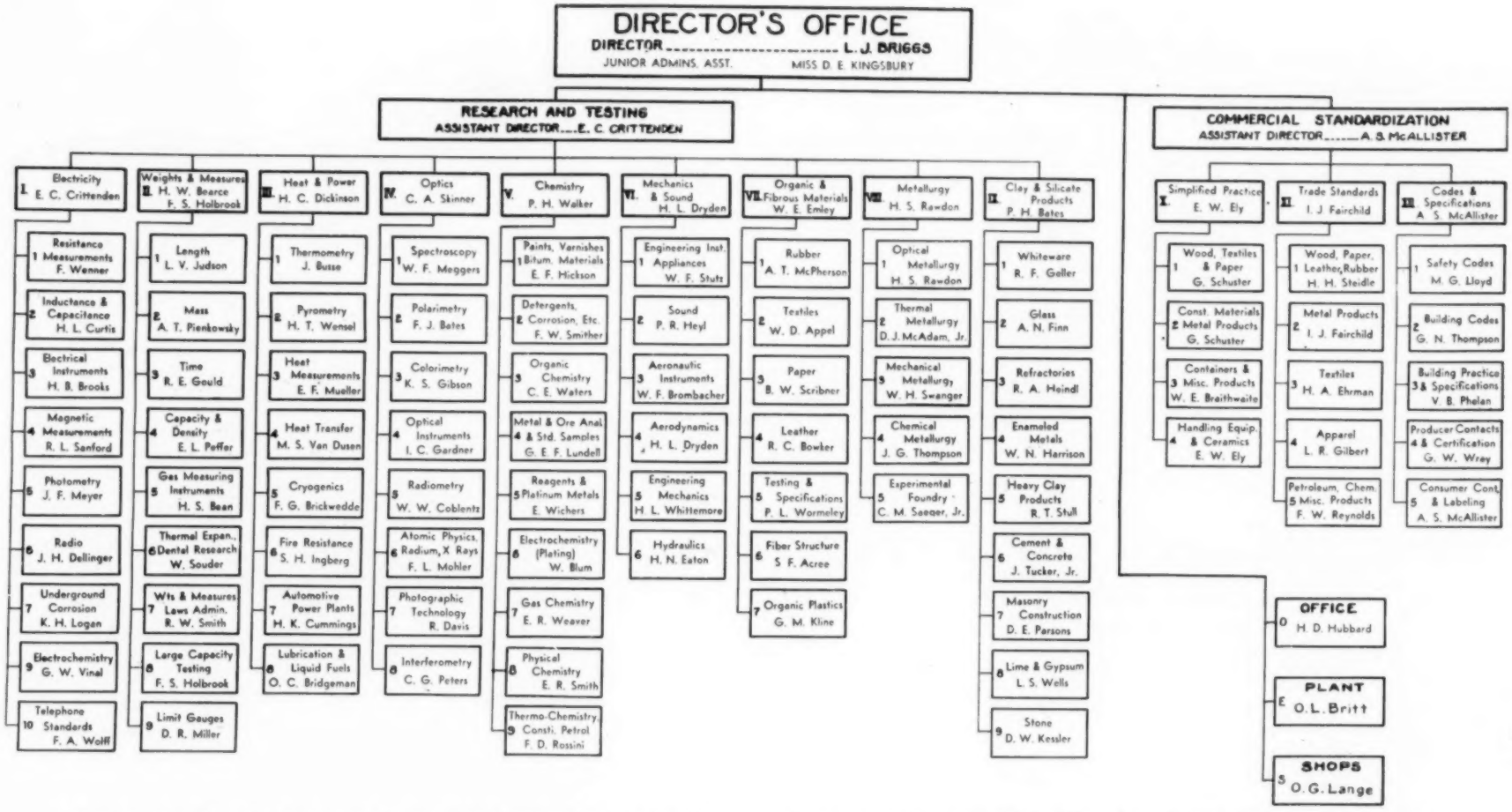
The service functions described above are necessary and important, and their nature is such as to require prompt attention to be effective. Their steady development in the face of reduced appropriations of recent years, has resulted in a drastic encroachment on time available for research.

Standards, as understood at the Bureau, are divided into five classes as follows: The fundamental standards of measurement, of which the standards of length, mass, and time are the most familiar examples; standards of quality, which usually take the form of a specification defining in measurable terms the desired properties of any material or article; standards of performance, such as specifications of the operative efficiency of machines and devices; standards of practice, such as safety codes for the electrical and other industries; and physical constants.

Organization

On the establishment of the Bureau in 1901, Dr. Stratton became its first director. In addition to Messrs. Wolff and Fischer, he secured the services of a notable group of young men to help him build the new Bureau on a foundation of real service to the country. Dr. E. B. Rosa was placed

National Bureau of Standards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3 Colorimetry K. S. Gibson
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5 Reagents & Platinum Metals E. Wichers
6 Electrochemistry (Plating) W. Blum
7 Gas Chemistry E. R. Weaver
8 Physical Chemistry E. R. Smith
9 Thermo-Chemistry, Consti. Petrol F. D. Rossini
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2 Sound P. R. Heyl
3 Aeronautic Instruments W. F. Brombacher
4 Aerodynamics H. L. Dryden
5 Engineering Mechanics H. L. Whittemore
6 Hydraulics H. N. Eaton
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6 Fiber Structure S. F. Acree
7 Organic Plastics G. M. Kline
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2 Thermal Metallurgy D. J. McAdam, Jr.
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3 Containers & Misc. Products W. E. Braithwaite
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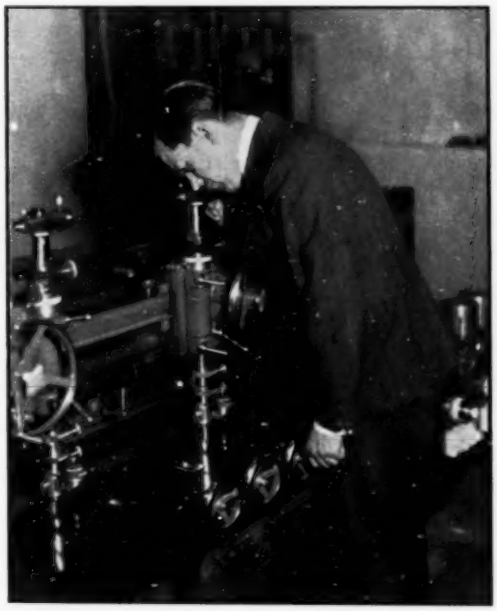
0 OFFICE H. D. Hubbard
E PLANT O. L. Britt
S SHOPS O. G. Lange

Organization chart for the research, testing and commercial standardization divisions (Revised to March 15, 1937) of the National Bureau of Standards.

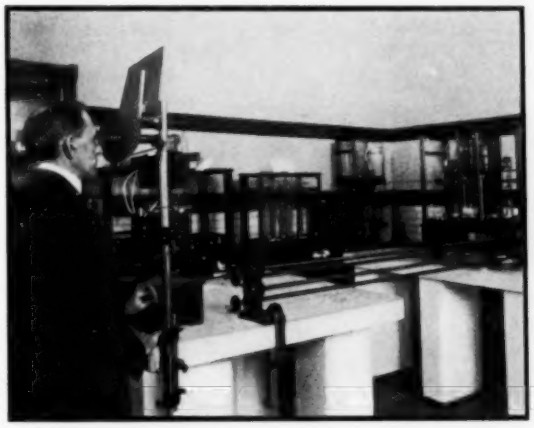
in charge of the electrical laboratories with Dr. Wolff specializing in electrical measurements. L. A. Fischer continued his work in weights and measures. Dr. C. W. Waidner directed the laboratories dealing with thermometry and heat measurements, Dr. W. A. Noyes was made chief chemist, and Dr. Stratton himself supervised the work in optics and what rapidly developed into the testing of miscellaneous instruments and materials.

Early in the history of the Bureau, it was decided that its organization should be based upon kinds of work rather than upon classes of standards. The activities of the Bureau were divided into certain major groups which soon became known as "divisions," the classification being made largely along academic lines, such as heat, electricity, optics, etc. Each division, in charge of a chief, was, in turn, subdivided into sections which became the working units, each dealing with some definite class of problems. In this way, men were placed in direct charge of the work for which they were particularly fitted by training, experience, and inclination. Yet, through this simple organization, with only two steps from director to section chief, each working unit was related closely to the others, and the cooperation of several sections could be secured when necessary.



L. V. Judson making a comparison of two line standards of length in the high-precision longitudinal comparator.

This divisional and sectional organization has been preserved in the main to the present day, and no better or more workable arrangement seems likely to be developed. The present organization is shown in the accompanying chart.



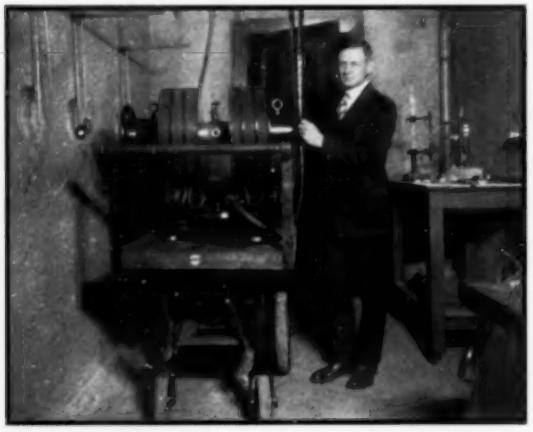
A. T. Pienkowsky using one of the high-precision kilogram balances. The long rods make it possible for the operator to stand at a considerable distance, thus avoiding temperature disturbances.

On the other hand, it was soon apparent that as the Bureau grew and the work became more diversified there was danger that one section might lose touch with the others. To avoid this, every effort has been made to bring the Bureau's "family" together in general meetings and discussions. Staff meetings are held, usually once a week, at which the problems of the Bureau are presented and discussed. Each division in turn is given the opportunity to present its work to the other members of the staff. Likewise, monthly reports are prepared by each section, which after examination by the Director, are circulated among the divisions.

Matters of policy were at first decided almost wholly by the Director, but as the Bureau grew and its activities covered an ever-widening field, the Director called more and more upon the different chiefs to aid him in determining matters of personnel, work to be taken up, and the presentation of results for publication. Today the meetings of the Director and his division chiefs are not unlike those of the president, vice presidents, and other officers of a corporation.

An unusual provision of the organic act creating the Bureau is that providing for a

visiting committee of five members appointed by the Secretary of Commerce, and consisting of men "prominent in the various interests involved, and not in the employ of the Government." This committee meets in Washington at least once each year. It studies the needs of the Bureau in the light of scientific and technical developments, and aids the Director and the Secretary of Commerce in presenting these needs to the Bureau of the Budget. The members of the present visiting committee are Gano Dunn, Karl T. Compton, M. E. Leeds, W. D. Coolidge, and F. B. Jewett.

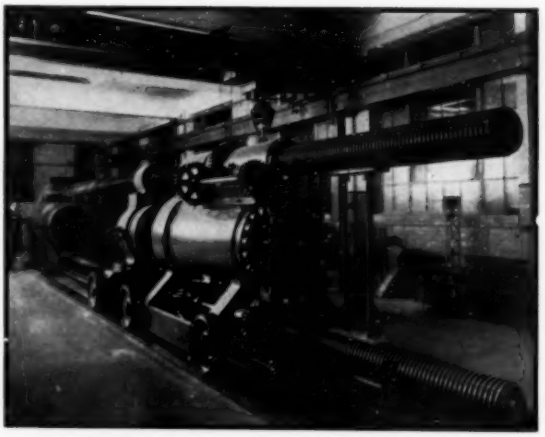


Large portable electromagnet used by Dr. W. F. Meggers of the spectroscopy section in studying Zeeman effects.

The staff of the Bureau originally numbering fourteen has now grown to eight hundred, approximately two-thirds of whom are men and women with scientific and technical training. All positions, with the exception of the Directorship, come under the Civil Service. The higher positions are filled, with few exceptions, by promotion from the lower grades.

Dr. Stratton remained as Director until December 31, 1922, when he resigned to accept the Presidency of the Massachusetts Institute of Technology. He was succeeded by Dr. George K. Burgess who had been with the Bureau since 1903, first as a physicist in the heat division, and later as the Chief of the Division of Metallurgy. Doctor Burgess served the Bureau with distinction until his sudden death on July 2, 1932. It was largely through his efforts that the so-called Research Associate Plan was developed. Under this plan a scientific or technical group may enter into a cooperative arrangement with the Bureau for the study of any problem in the Bureau's field, of fundamental importance to that group. In order to carry on the work, a research associate is appointed from among the men best qualified to conduct experiments along the lines desired. The associate's salary is paid by the group which he represents; otherwise, his status is that of a Bureau employee, and he works under the direction of some member of the regular staff. The results of the work growing out of a Research Associateship belong to the public and are published by the Bureau either in its own *Journal of Research*, or in the appropriate scientific or technical journals. As many as one hundred Research Associates, representing fifty scientific or technical groups, have been assigned to the Bureau at one time. The plan has enabled industries not well provided with research laboratories to benefit from the Bureau's facilities with the minimum disruption of the Bureau's staff and research program.

The vacancy in the Directorship resulting from the death of Dr. Burgess was again filled by an appointment from the Bureau staff. Dr. Lyman J. Briggs, the present Director, was formerly assistant director of research and testing and chief of the division of mechanics and sound.

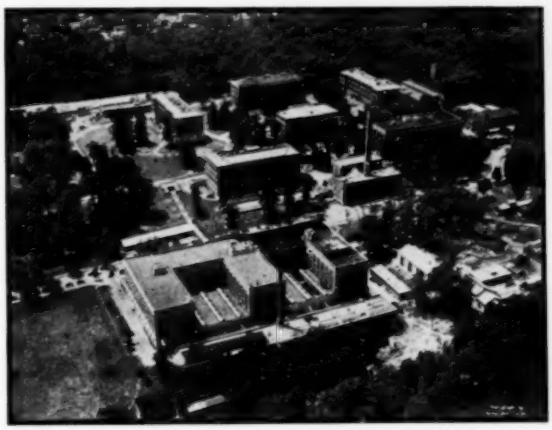


The emery high-precision horizontal testing machine. Capacity, 2,300,000 pounds in compression; 1,150,000 pounds in tension.

The assistant directors are Mr. E. C. Crittenden, who is also chief of the electrical division, and Dr. A. S. McAllister, who is also chief of the division of codes and specifications.

Laboratory Facilities

The site of the Bureau is on high land near Connecticut Avenue in Washington, about four miles northwest of the White House. Selected originally as being free from mechanical and electrical disturbances, the city has since grown beyond and around it. To protect against this encroachment and to provide space for necessary additional buildings, the reservation has since been enlarged through various purchases to 56 acres. There are now 12 major and 7 minor permanent buildings, harmonious in external appearance, each of which has been designed for the work it is intended to house. Thus, the South Building is constructed with very heavy walls and with several underground laboratories where temperature changes are reduced to a minimum. One end of the Electrical Building is constructed of nonmagnetic material with all reinforcement of special alloy steel and all piping of brass or bronze. The Industrial Building, on the other hand, is purely a factory-type structure but is well suited to house the large testing machines, textile, paper, rubber, and leather laboratories, and the optical glass plant.



Airplane view of the National Bureau of Standards. There are 19 permanent buildings on a site of 56 acres, in the northwest suburbs of Washington.

The laboratory equipment is, in general, well suited to the work, although in some cases the demands of science and industry have run far ahead of the Bureau's facilities. Because of electrical disturbances it is impossible to carry out some of the radio work in the original laboratory. Field stations have, therefore, been established in nearby Maryland for transmission of standard radiofrequencies, and for studying radio transmission phenomena. The small high voltage laboratory is now inadequate and the Bureau finds itself in the unfortunate position of being unable to test some of the transformers and other equipment used in connection with high voltage electrical transmission. The same is true of high potential x-ray equipment. Ultimately, better provision must be made for the testing of structural materials. The equipment of the cryogenic laboratory is also far from adequate. Rooms deep underground are needed for many lines of work, and the lack of humidity control in summer interferes with precise electrical measurements. Despite these deficiencies, the Bureau's buildings and equipment as a whole probably compare favorably with those of other national laboratories, and some features are unusual. For example, the possession of a testing machine with a loading capacity of 10,000,000 pounds has made it possible to carry out an extended study of the behavior of columns and other parts of the largest buildings and bridges under full load. The Chemistry Building and the recently completed Hydraulics Laboratory are examples of buildings planned with care by the men who were to use them. The former building has been visited by chemists from all over the world and many of its features have been incorporated in the designs of other laboratories. Most of the Bureau's buildings are connected by tunnels with the central power plant. These tunnels carry the numerous pipe lines and electrical trunk lines, and as they are large enough to walk through comfortably, they are widely patronized in stormy weather.

The Bureau has always endeavored to test materials and equipment in ways approaching as closely as possible those of actual use. This has led to the installation of special testing equipment and of semi-commercial plants where the behavior of the materials may be studied under controlled conditions, closely approximating those met in service. Thus, there are altitude laboratories for the study of airplane engine performance under flight conditions; equipment for accelerated weathering tests of paints, var-

nishes, and other protective coatings; wind tunnels for calibrating aeronautic instruments and studying the distribution of wind pressure on models of buildings, trains, and automobiles; plants for the fabrication of rubber goods, the making of paper, cement, and optical glass.

In the case of certain Government testing, particularly cement and miscellaneous building materials, it has been found necessary to establish small branch laboratories in the localities in which the products are manufactured or are to be used. The Bureau maintains permanent branch testing laboratories at Northampton, Pa., Denver, Colo., and San Francisco, Calif., and sets up temporary facilities from time to time in the vicinity of large construction projects of the Government.

F. G. Brickwedde, and apparatus used in the liquefaction of helium.

Present Work

While the field of activity of the various divisions and sections is indicated in the organization chart, a few examples of the current work of each of the divisions may be of interest. Since its early days the Division of Electricity, now under the direction of E. C. Crittenden, has been concerned with the precise determination of the values of the electrical units. The Bureau is one of the national laboratories selected by the International Committee on Weights and Measures to carry out the necessary determinations for placing these units on an absolute basis. It has published values for the ampere and ohm in terms of the present international values, and is continuing the work. The basic phenomena governing radio transmission have been the subject of extensive investigation. Continuous measurements of the height of the ionized layers, many miles above the surface of the earth, form a regular part of the Bureau's program. Recently, a new phenomenon, a complete fading out of radio signals of certain wave-lengths for short periods, has been found to be connected with eruptions on the sun's surface. Standard frequency radio signals are broadcast on a regular schedule and serve to standardize control equipment in transmitting stations and laboratories. Many tests of electrical instruments, batteries, cables, etc., are made by this Division for the Government and for manufacturers.

The wide variety of testing and investigational work of the Division of Weights and Measures is handled by co-chiefs H. W. Bearce and F. S. Holbrook. Improvements are being made in methods of measuring length and in the construction of precise mass standards. The Bureau's comparators for line standards of the order of a meter are regularly used with an uncertainty of less than one part in a million. Methods developed in this Division for the construction and graduation of precision circles used on theodolites of the Coast and Geodetic Survey have aided the Survey in carrying out its first-order triangulation of the country. The identification of forgeries for other Federal agencies has saved the Government millions of dollars. Without resort to regulatory power, much has been accomplished in bringing about the practical uniformity in weights and measures which exists throughout the United States today. Each year a conference of state, municipal, and other weights and measures officials from all parts of the country is held at the Bureau. At these conferences current problems are discussed and proposed uniform laws and regulations are drafted. This Division also has charge of the Bureau's equipment for testing master scales, which in turn are used by railroads to check the heavy weights employed in testing railroad track scales. A recent acquisition is a truck carrying 15

1000-pound weights, handled by a power crane, which is used to test the platform scales of the Government and to aid the several States by making surveys of existing conditions.

The Heat and Power Division, under the direction of Dr. H. C. Dickinson, is charged with the maintenance and extension of the international temperature scale. Work on the extension of the scale below the oxygen point is now in progress. The certification of thermometers, thermocouples and pyrometers in terms of the international scale is an important service function of this division. Research on the properties of steam is being continued as a part of the program to provide international steam tables. The properties of materials at very low temperatures, including the superconductivity of metals, are being investigated, and the fire resistivity of building materials is being studied in specially constructed test-houses and furnaces. Detailed study of the properties of fuels and lubricants in internal combustion engines is under way.

In the Optics Division under the supervision of Dr. C. A. Skinner the study of spectral lines as secondary wave-length standards in the ultraviolet is being continued. Interferometry is being used in the construction of precision length standards, as, for example, decimeter end-standards of fused silica which are believed to be accurate to 1 part in 5,000,000. Other lines of work include the optical properties of the sugars and the supervision of the sugar analyses of the customs laboratories of the Treasury Department; the measurement of the spectral distribution and intensity of x-rays for therapeutic purposes; the measurement and certification of practically all the radium sold in this country; the development of a rational system of color standards; and the study of methods for the measurement of ultraviolet radiation in sunlight and artificial sources

The work of the Chemistry Division, headed by P. H. Walker, includes a great amount of testing for the Government, as well as research on petroleum, pure rubber, methods of analysis of metals and alloys, electroplating, and gas appliances. A group of 10 research associates supported by the American Petroleum Institute is engaged in the study of the composition and characteristics of lubricating oils. Sections dealing with physical chemistry and thermochemistry have recently been established. An important function of the chemistry division is the preparation and distribution of carefully analyzed samples of metals, alloys, ores, and other materials. These samples have been of great value in bringing about the adoption of uniform methods of analysis in commercial laboratories.

In the Mechanics and Sound Division, under the direction of Dr. H. L. Dryden, water current meters are calibrated in a flume 400 feet long with the aid of a traveling carriage running the length of the flume. The sound-absorbing qualities of acoustic tiles and plasters are measured at various frequencies in a large windowless room with highly reflecting walls. Methods have been developed for measuring the turbulence in wind tunnels and of relating the results of drag measurements secured in different tunnels. Aeronautic instruments are developed and tested. Recent work on the strength of various designs of rigid frames points the way to very substantial savings in this type of construction. The work of the hydraulics laboratory has dealt largely with pressure losses at pipe bends and the scour of river beds. A large staff from the Soil Conservation Service is also working in this laboratory.

The Organic and Fibrous Materials Division under the direction of W. E. Emley has given much attention to the development of accelerated service tests of materials, and is equipped with several ingenious machines for carrying on work of this kind. Among these may be mentioned those for determining the durability of sole leather, of shoe uppers, hosiery, carpets, and automobile tires. The work of this division is concerned primarily with textiles, paper, leather, rubber, plastics and the utilization of waste materials for industrial purposes. A very large amount of routine testing is done for the Government.

The Division of Metallurgy under the direction of H. S. Rawdon has given much study to the behavior of metals under load at both high and low temperatures, and of the failure of mechanical parts, such as airplane propellers under repeated vibration. The corrosion of light alloys and their protection has also received much attention. The study of commercial uses for silver has just been inaugurated under the

research associate plan, with the cooperation of several universities. The division's equipment includes furnaces, rolling mills, a forging press, a drawbench, and an experimental foundry.

The work of the Division of Clay and Silicate Products directed by P. H. Bates covers a broad field. It includes the study of domestic materials for use in the production of whiteware, industrial porcelains and other clay products, the fundamental constituents of portland cement, the behavior of concrete during setting including the heat of reaction, the causes of failure of enameled metal ware, and the weathering of stone. Over 4,000,000 barrels of cement were tested for Government use last year. All of the optical glass required by the Navy is made in the Bureau's glass plant. Improved methods for producing glass have been developed and the time necessary for making it has been cut down.

A considerable part of the research work of the scientific and technical divisions is conducted in cooperation with other Governmental agencies, notably the Navy Department, the National Advisory Committee for Aeronautics and the Bureau of Air Commerce.

Turning now to the commercial standardization group, the objective of the Division of Simplified Practice, under the direction of E. W. Ely, is to reduce costs through the elimination of unnecessary sizes and varieties in a line of manufactured products. Thus, paving bricks have been reduced from 64 sizes to 6. The action is wholly voluntary, and the decision is reached through a joint conference of manufacturers, distributors and consumers. About 160 simplified practice recommendations have been promulgated by the Bureau, and trade association officials state that they have resulted in the saving of many millions of dollars.

The next step is the establishment of a standard of quality for a product. This procedure is carried out by the Division of Trade Standards, under the direction of I. J. Fairchild. Typical examples are wood shingles, oak flooring, plumbing fixtures; interchangeable ground-glass joints and stopcocks. As before, the commercial standard is arrived at voluntarily through a joint conference of manufacturers, distributors and consumers. In both divisions also the written acceptance of a substantial majority of the groups concerned is required before a recommendation or standard is promulgated. Honest informative labeling of products, certifying conformance with some designated commercial standard is encouraged, because experience shows that honest labeling helps both the consumer and the producer.

The Division of Codes and Specifications under the direction of Dr. A. S. McAllister is concerned with the development and use of nationally recognized codes for the safety of industrial workers. It is also endeavoring to develop a nationally recognized building code, because uniform building and plumbing codes in all municipalities would contribute measurably to the reduction of building costs. This work is being carried out under the procedure of the American Standards Association. The Division also encourages the use by tax-supported agencies of recognized specifications in making purchases. To this end it supplies lists of manufacturers who certify their readiness to supply goods meeting these specifications. A directory of college and commercial laboratories equipped to make tests of these products has also been compiled.

The Bureau does not make tests of supplies for nongovernmental agencies if other laboratories are equipped for such work. Tests for outside agencies are limited almost entirely to the comparison of measuring instruments with the national standards. Fees received for this work are not available for its further support and are sent to the Treasury as miscellaneous receipts.

The results of the Bureau's research in science and technology are published each month in the *Journal of Research of the National Bureau of Standards*. Each number of the Journal contains on an average a dozen original papers. It is sent to a carefully selected mailing list of libraries in this country and abroad, and is also obtainable on a subscription basis. The reports in the Journal are later issued as individual research papers.

In addition to the *Journal of Research*, the Bureau issues a monthly *Technical News Bulletin*. This contains abstracts of reports in the journal and describes work in progress in the laboratories, and also contains a complete list of all publications by members of the Bureau's staff whether published in the Bureau's own series or in scientific or technical magazines.

Uses and Limitations of X-Ray Diffraction Methods*

By JOHN T. NORTON**

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Cambridge, Massachusetts

SINCE the time of the celebrated experiment of von Laue which demonstrated the process of diffraction of x-rays, this phenomenon has been of the greatest importance to the student of metal structures. The potential possibilities of x-ray diffraction as a means of solving some of the complex problems which perplex the metallurgist are tremendous and there have been some notable successes which have assisted greatly in advancing our knowledge of the metallic state. On the other hand, the success of the method as a practical testing tool has fallen somewhat short of the hopes and expectations of many of those interested in its development. There are several reasons for this situation which will be discussed, but for the moment it seems advisable to consider the sort of information which can be obtained and the general type of problem to which diffraction methods are applicable.

Metals are crystalline substances and almost all properties which make metals so valuable as engineering materials have some degree of dependence upon crystal structure. It has been said that the perfectly enormous variety of metallic properties which are observed is merely an expression of the variety of ways in which the atoms of the metallic elements may be put together. It is to be expected, therefore, that the atomic arrangement in a particular alloy should play a leading part in determining its behavior and experience has amply confirmed this fact. It is only comparatively recently that the importance of this fundamental concept of the metallic state has begun to be generally understood by metallurgists, largely due to the clarification of the picture by x-ray diffraction studies.

It is not correct to suggest that x-ray methods have developed a new picture of metallic structures, but rather that they have assisted the many other methods by indicating a new approach to an old problem. It is believed that our present ideas of the metallic state are quite independent of the methods used in obtaining information. More and more, these ideas are being extended to the interpretation of engineering problems.

Professor Norton gives here a critical analysis of the usefulness of x-ray diffraction equipment as an industrial tool. He emphasizes the need for intelligent direction by someone who not only understands the nature of the information to be gained but who also has the ability to resolve metallurgical problems into their fundamental aspects.

X-ray diffraction methods are valuable only if the results can be expressed in terms of physical properties. The interpretation of the observations is really a two-stage process. The direct diffraction evidence

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supplied by the sample consists simply of dark spots on a photographic film which are traces of interference maxima whose size, shape, and distribution with respect to known directions are measurable. Extensive investigations have shown that this direct evidence may be interpreted in terms of the atomic arrangement in the metal, that is, the atomic environment in which each atom finds itself. The expression "atomic arrangement" has a broad meaning in this connection. Primarily it signifies the type of lattice which describes the positions of the atoms of the crystal and the distances separating neighboring atoms. In addition, however, it refers to the orientation of the crystal with respect to known directions, the number of crystals in the area illuminated by the x-ray beam, the relative orientation when there are several crystals and finally, the perfection of the crystal lattice or its departure from ideal crystallinity. This is the first stage in the process.

The second stage in the interpretation of the diffraction evidence is of more general interest to the metallurgist. This consists in the translation of the first part of the evidence into a form which is useful in the explanation and prediction of the physical properties of metals. A few examples will make this clear. Suppose one is investigating the distortion of a large grained sample under repeated stress. Certain surface observations as to the mechanism of deformation become significant only if the orientation of the grain is known. This information is rapidly and accurately obtained from the study of a back-reflection Laue photogram.

Another example is given by the situation encountered when a phase precipitates from a homogeneous solid solution. The microscope shows that this precipitation is confined to the immediate neighborhood of the grain boundaries. The question arises as to whether the effect is a local one and only regions close to the boundary have reacted or whether the reaction has taken place throughout the grain and the precipitated particles have migrated to the grain boundaries. Obviously a determination of the composition of the solid solution will answer this question and the composition is quickly determined by measuring the lattice parameter. If the parameter is that of the super-saturated solid solution, then the precipitation is very local for the diffraction pattern is determined by the dominant phase. On the other hand, if the parameter is that of the equilibrium solid solution, then precipitation has been followed by migration. Broad diffraction lines would indicate a range of composition from the center to the edges of each grain showing that the precipitation and migration were only partially complete.

Still another example has to do with directional properties in sheet metal subjected to a cycle of working and heat treatment. The question is whether these directional effects are due to grain orientation or to the distribution of certain discontinuities such as impurities at grain boundaries or inclusions. X-ray diffraction information will provide, by means of pole figures, a statistical picture of the orientation of a large number of crystal grains and from a knowledge of the directional characteristics of the crystals themselves, a fair prediction can be made of properties of the aggregate. A comparison of this prediction with the observed properties will give an estimate of the importance of the impurities or inclusions.

The study of crystal distortion as the result of microscopic systems of stress serves as still another illustration. Such distortion is indicated by broadening of the diffraction interference maxima and fairly precise comparisons may be made. Controlled experiments will establish the relation between this line broadening and the mechanical and thermal treatment of the specimens. Many physical properties are influenced by the presence of such stress systems and the relation of these properties is much more clearly understood if a picture of the lattice distortion is available. The problem of stress relief in cold worked metals and in welded structures is a situation which is being successfully handled in this way.

It is not intended to discuss the theoretical aspects of x-ray diffraction in this paper or to elaborate upon apparatus and experimental techniques for this has been well done elsewhere. It does seem desirable, however, to outline the basic types of information which may be obtained by x-ray diffraction so that one unfamiliar with x-rays can appreciate the fields in which this information might be useful. The direct information may be classified into the following four groups:

1. Type and Size of Crystal Lattice

The lattice types and parameters of all pure metals, of a tremendous number of binary phases, and many ternary and quaternary phases are now known. The principal use of this type of diffraction information at present and in the future will be in the identification of metallic phases present in an alloy. In many cases a complete structure determination is unnecessary, for the diffraction pattern itself is a unique representation of the structure and can be compared with patterns of known structures until a match has been found. Some laboratories have prepared an extensive catalog of photograms and unknowns can be rapidly located by a system of classification similar to that used for finger prints.

There are many instances where the interest is in the change in lattice dimensions, when the type of lattice is known or at least does not change during the experiment. Examples are the determinations of phase boundaries and the progress of reactions in the solid state. Here again it is not necessary to know the structure completely because any parameter of the lattice will serve for purposes of comparison. Frequently when the crystal does not change symmetrically with composition, the most sensitive parameter is chosen for observation.

Small quantities of a phase cannot be studied in the presence of large quantities of another phase by observations made on the whole sample. Some method of isolation or concentration of the minor phase must be employed and there are many examples of this procedure in the literature. The unsatisfactory nature of these processes constitutes one real limitation of the diffraction method. Observation of phases which exist at elevated temperatures can be made and this practice is increasing. The examination of quenched samples at room temperature introduces certain undesirable uncertainties.

2. Crystal Orientation

The orientation of important lattice directions in single crystal and large grained polycrystalline samples can be determined in several ways, chief of which is by the use of the back reflection Laue pattern. A pattern of this type is easily interpreted and gives simple, direct and accurate results. The orientation relationships in fine grained aggregates can also be studied. The most common and probably the best method of representing the situation in the fine grained sample is by means of a pole figure. A

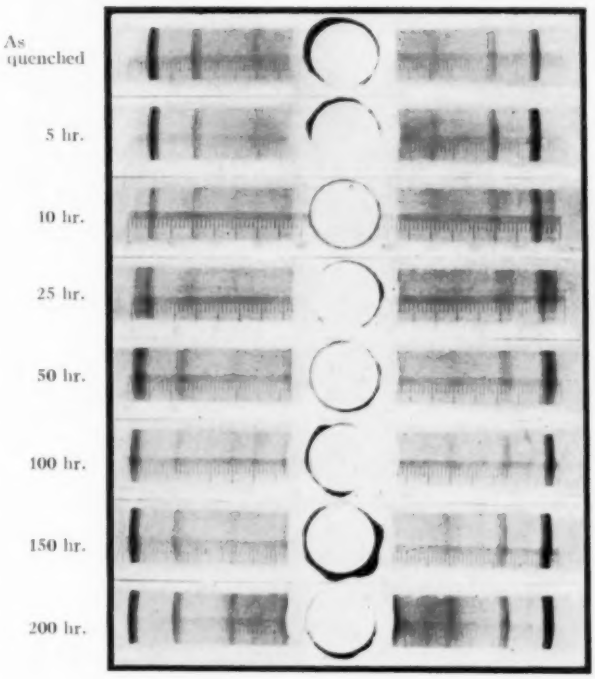

FIG. 1. X-ray diffraction photograms showing change in composition of a solid solution. The alloy is magnesium containing 9.6 percent of aluminum quenched from 415°C and aged at 175°C for the time indicated. As the aging progresses, the aluminum content drops from about 9 percent to about 3 percent, but at the intermediate stages, the broad lines indicate a range of composition existing in the sample.

number of photograms are made at different angles and the intensity maxima are combined in a stereographic projection which gives a statistical picture of the distribution of some important crystallographic direction averaged over a considerable number of grains. Such determinations involve a great deal of work, but after the necessary tables and charts are prepared, the work progresses quite rapidly. No other mode of representation gives as complete a picture. A characteristic type of interference maxima known under the general term of "asterism" is indicative of the orientation relations produced by fragmenting metal grains.

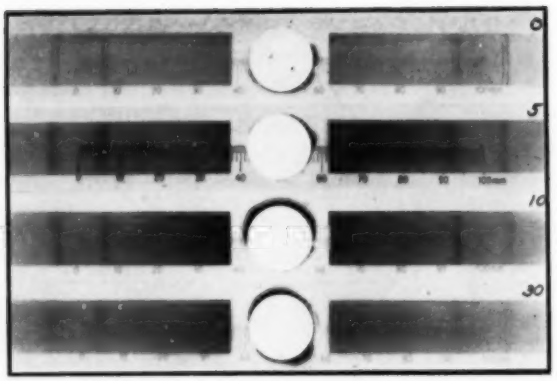

FIG. 2. Back reflection photograms of brass cold worked by pressing. The numbers represent the degree of reduction and the progressive broadening of the diffraction lines is obvious. The broadness is measured quantitatively and when related to the degree of cold work, can be used to measure cold work in other samples.

3. Grain Size

X-ray diffraction methods offer a means of making comparative measurements of grain size. This is done by determining the number of interference maxima due to individual grains in a certain area of the sample. The grain size must be smaller than the size of the x-ray beam and larger than a critical value at which the individual maxima are no longer resolved. This is a sensitive method of determining recrystallization temperatures. For the study of very small grain sizes, methods have been devised which depend upon the broadening of the interference maxima. These methods are generally unsatisfactory for polygrain metals because of the uncertainty as to amount of distortion of the grains themselves, and it is rather dangerous to apply them for studying such problems as grain size in cold worked metals. If one can be reasonably sure that the grains are unstrained and homogeneous in composition, good comparative results are possible.

4. Crystal Distortion

The study of the interference maxima in an x-ray diffraction picture indicates a good deal about the perfection of the crystal lattice. The diffraction process is a great integrator of lattice defects on an atomic scale, but if the perfection of the ideal lattice is disturbed on a somewhat larger scale, the effects are observable. A uniform distortion of the lattice such as would be produced by a uniform elastic stress causes the interference maxima to shift without loss of sharpness. This is the basis of the method for the direct measurement of elastic stress. On the other hand, if the distortion is not uniform within the area of the x-ray beam, the maxima are broadened. Such broadening is seen in cold worked samples. The line broadening determined by visual inspection or by measurement from densitometer curves given an excellent indication of the internal condition of a metal sample. Care must be taken, however, that this effect is not due to a local variation in composition of the phase giving the diffraction pattern or that the sample is not of extremely fine grain as both conditions produce broad maxima. Broad lines from an electrodeposited layer for instance, would not necessarily indicate elastic strain unless the other possibilities were eliminated.

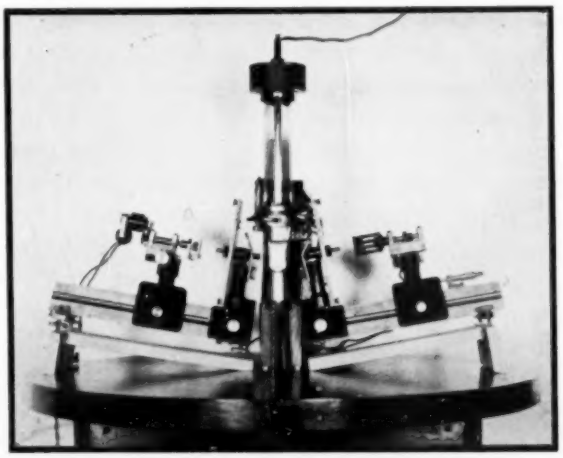

FIG. 3. A gas or ion type x-ray tube set up with two back reflection cameras.

These are the four basic types of information which can be obtained by x-ray methods. The task of the metallurgist is to see where such information can be applied. If the problem under investigation can be analyzed thoroughly and it appears that some of the information cited above would be helpful in its solution, then diffraction methods will be used. If crystallographic evidence properly interpreted does not seem to apply, then attention should be directed to other methods.

Obviously no set of specifications can be laid down as to the problems which can be solved by diffraction methods. Frequently the conditions

involved in a particular problem are not sufficiently known so that the results of x-ray experiments can be predicted and one can only try and see what comes out, provided the importance of the problem warrants such a chance. But in any case, until the problem is resolved into its fundamental aspects it is impossible to decide upon the value to be obtained from such a means of investigation.

With the increased use of diffraction methods, it is to be expected that many new developments in technique and apparatus would result. Some remarks concerning new features seem desirable. Regarding the x-ray source, two conditions are interesting. One is the increasing use of ion type tubes for laboratory installations. These tubes are constructed inexpensively in the laboratory work shop, provide for a rapid change of targets and give a dependable and intense beam of x-rays. A tube of this type is shown in Fig. 1. Another development is the small, but powerful self-contained unit which is now appearing using a sealed-off electron tube. Fig. 2 shows an example. This unit would have many applications in the metallurgical laboratory.

Interference maxima occurring at large diffraction angles are used to an increasing degree in several types of camera. The symmetrical focusing camera can be used as an absolute instrument for very precise parameter measurements. The Sachs camera shown in Fig. 3 is extensively used for measuring parameter changes and for studies of line broadening. It has the great advantage of using a solid sample with a flat surface. Quantitative measurements of line broadening with the aid of a microdensitometer are becoming more frequent. The back reflection camera using general or white radiation is the most satisfactory method of determining the orientation of crystals.

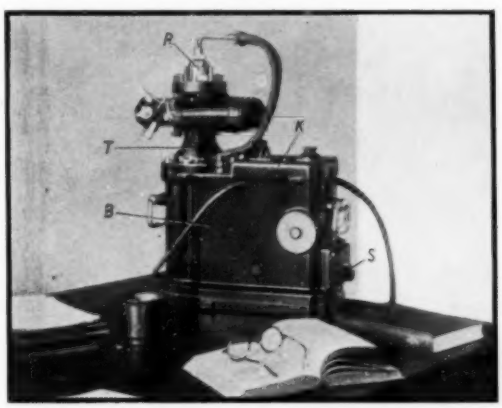

FIG. 4. A small self-contained x-ray unit for diffraction showing three cylindrical cameras in place.

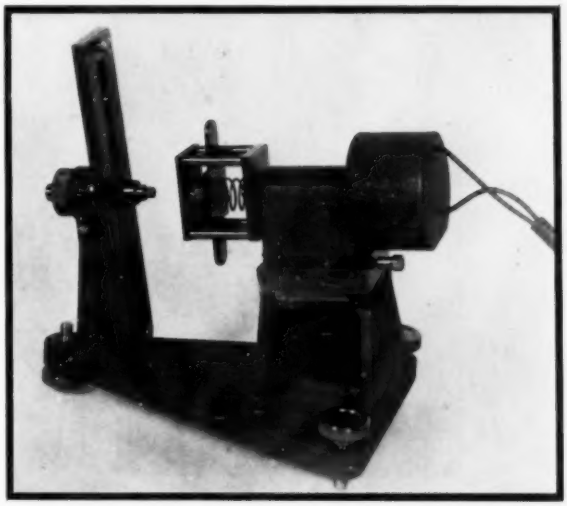

FIG. 5. A new model of the Sachs camera employing the back reflection principal.

For the identification of phases, some investigations have combined a crystal monochromator with the diffraction camera to very good advantage. The purity of the resulting radiation is such that the photogram is greatly improved, particularly at small diffraction angles and the added clarity quite makes up for the increased time of exposure. The difference in the photograms due to this effect is very striking.

The use of the pole figure is being extended in the study of problems of preferred orientation and its significance is much more generally appreciated than was the case a few years ago. A machine for plotting such a figure mechanically is a recent development.

Another recent development of considerable interest is a method for the direct measurement of elastic stress by x-ray diffraction. The stress produces a change in the parameters of the lattice and these changes are recorded by a shift of the lines on a film. Two photograms, one normal and one oblique to the surface are required to calculate the directions and magnitudes of the principal stresses at the surface. This method has been applied in Germany to the measurement of stresses in columns and beams,

and in this country the stress distribution in tubes which have been expanded by internal pressure is being investigated. No very great precision is possible at present, but the German

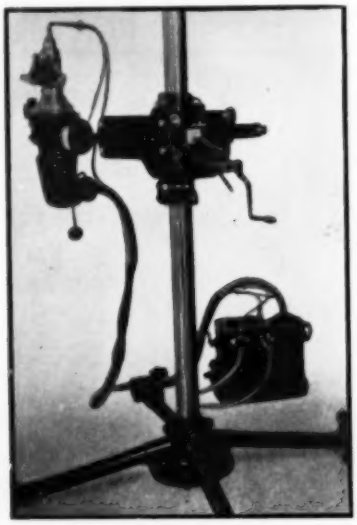

FIG. 6. X-ray diffraction apparatus for measuring elastic stress. X-ray tube and camera form a single unit.

workers claim an accuracy of about 1000 pounds per square inch in steel. Fig. 4 shows the apparatus which may be employed in which the x-ray tube and camera constitute a single unit. It has applications where other methods cannot be applied.

It frequently has been emphasized that the success of a military operation depends more upon the gunners than upon the guns, and this same philosophy may be applied to the use of diffraction methods. It is definitely not a process in which the samples can be placed in a hopper, the crank turned and the results in finished form come tumbling out the other end. There is considerable amount of routine work, to be sure, and with modern equipment and methods, a great deal can be done with relatively inexperienced personnel. However, there must be some one directing the work who has not only a thorough knowledge of the information which can be obtained from diffraction methods, but also the ability to resolve the metallurgical problems which arise into their fundamental aspects.

Many engineers believe that the user of diffraction methods has a special x-ray point of view about metals which differs radically from that held by anyone else. This is not true, at least in the majority of cases. What he has and must have if he is to be successful is a fundamental point of view of the crystalline nature of metals. He applies to the problem at hand whatever methods seem best suited after it has been properly analyzed. The diffraction method is only one of the tools which he has in his extensive kit. It is essentially a research tool, but so are many of the others which have produced practical results. It is true that there have been enthusiasts who have been interested much more in x-ray technique than in physical metallurgy and possibly this has given an improper emphasis to the situation. But the same criticism may be leveled at those who have labored hard and long in the development of some other method of investigation such as the tensile test and who should not be judged too harshly when they are inclined to feel that, after all, the tensile test is really the only way to study a metal.

X-ray diffraction methods have not been extensively used as a practical testing tool because they have supplied information which was of a more fundamental character than that generally employed in solving practical problems. As metallurgy becomes more and more an exact science, fundamental concepts will play a greater part and we may expect to find an increasing use of these methods. If they are to take their proper place, however, they must be directed by those who have a thorough understanding of their uses and limitations.

A Lightning Flash

and

Its Component Strokes

By JOHN G. ALBRIGHT

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IN 1889, C. V. Boys made the assertion that lightning flashes were very often multiple, two, three, or many more strokes succeeding one another very rapidly along exactly the same path. To test this assertion, H. H. Hoffert[1] exposed a camera during a thunderstorm in the direction in which frequent lightning flashes were seen, and kept it wagging rapidly to and fro. He obtained three separate images of the flash, widely separated, but identical in form. In 1905, B. Walter[2] of Hamburg obtained pictures of the multiple structure of lightning with a camera rotated by clockwork. Later[3] he used three cameras in photographing lightning, one of them rotated by clockwork, and two fixed cameras two meters apart, to obtain stereoscopic pictures. His best known pictures[4] were taken in 1918 when he used a rotating camera and a stationary one. These pictures showed a multiple structure, with branching only on the first stroke.

A. Larsen[5] of Chicago took pictures of lightning flashes, using a revolving camera, and observed the multiple structure. He also noted that the first component stroke only was forked; it was forked downward indicating that the cloud was charged positive with respect to the earth. A. Steadworthy[6] of Toronto, Canada, took pictures showing the multiple structure of lightning as well as the spectrum of the flashes.

Later, E. C. Halliday[7] and B. T. J. Schonland[8, 9] used a camera invented by C. V. Boys[10] to take pictures of lightning flashes. This camera employs two lenses with axes parallel about four inches apart. The lenses are rotated about an axis half-way between with an angular velocity of about 1500 revolutions per minute. The plate is fixed and the images formed by the lenses travel in a circle upon it.

Schonland has been able to measure the velocities of the "leader stroke" and the velocities of the main stroke separately, and has found that the velocity of the leader stroke was approximately one-fifth that of the main stroke. He obtained velocities of the leader strokes averaging about 8×10^8 cm/sec., and for the average velocity of the main stroke he obtained about 45×10^8 cm/sec.

Using a camera with two stationary lenses and two right angled prisms, pictures were taken in 1934 upon a swiftly moving film by W. L. Lloyd and W. A. McMorris[11] which showed a flash with ten components. The first component only showed forking, while all the others were accompanied by leader strokes. Velocities of both leader strokes and main strokes were measured, showing velocities agreeing very closely with those obtained by Schonland.

More recently, E. J. Workman, J. W. Beams and L. B. Snoddy[12] have also used cameras with fixed lenses and with the film carried on a rotating drum at speeds up to 850 cm/sec.

The rotating camera used by B. Walter[2–4] resolved the lightning flash into its component strokes, but rotated too slowly to produce any separation of the leader stroke and the main stroke. The lenses of the Boys camera[7–10] can be rotated fast enough to get excellent resolution of the leader stroke and the main stroke, but since the images of the strokes are moving endwise for a great part of the circle, the photographs of the component strokes get hopelessly confused in that part of the circle. The apparatus used by Workman[12] is capable of a high degree of resolu-

tion without the confusion introduced by the Boys camera. All these methods, however, have one difficulty in common, that of training the

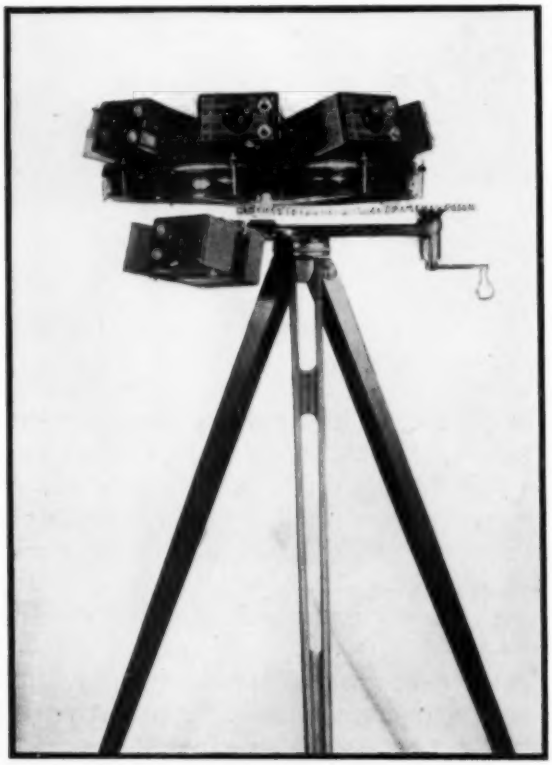

FIG. 1. Side view of apparatus showing drive.

camera on the expected flash. It is difficult to anticipate the position and time of the expected flash and to have the apparatus in operation and trained on the position at the proper time. Boys[10] stated that he had not obtained a single photograph with his camera after twenty-five years of endeavor, and despaired of ever getting one.

To overcome the difficulty of training a single camera on the expected lightning flash, the author designed and built the apparatus shown in Fig. 1. It consists of eight cameras mounted on a revolving disk, facing out, forty-five degrees apart, so that they completely cover the horizon. Box cameras are used, size $2\frac{1}{2}$ inches by $4\frac{1}{4}$ inches, each camera covering an angular field of about sixty degrees; and since they are set forty-five degrees apart, their fields overlap. The axes of the cameras are elevated about twelve degrees, obtaining a better view of the sky and taking in less of the foreground.

The disk carrying the eight cameras is mounted on a bicycle wheel equipped with a coaster brake, and the spindle of the wheel is mounted vertically on a tripod. The wheel is driven by a chain from a large sprocket fitted with a crank, and is geared to make two revolutions to one of the crank.

Besides the eight cameras mounted on the revolving wheel, three cameras are mounted on the lower side of a plate below the wheel. The three cameras remain fixed and cover about 150 degrees of the horizon. They, also, are elevated to about twelve degrees and are used to take "still pictures" of the lightning flash for purposes of comparison. Fig. 2 is a front view of the apparatus showing the three stationary cameras mounted below the revolving cameras.

In preparation for observations, the apparatus is mounted on some elevation, such as the flat roof of the physics building at Case School of Applied Science, where a clear view of the entire horizon can be obtained. The tripod is fastened to a wooden frame which is held secure to the flat roof by sand bags. After all the cameras have been loaded with film, a tarpaulin is tied over the apparatus and a suitable thunder shower is awaited. The compact thunder showers that develop in summer from cumulus clouds produce suitable flashes for observation, but since the shutters of the cameras must remain open for a considerable period, only the storms that occur during the darkness of the night can be observed.

As it is important to know the angular velocity of the whirling cameras, a metronome is used which ticks half-seconds, and the crank is turned in unison with it. Since the wheel makes two revolutions to one of the crank, the disk with its eight cameras makes four revolutions per second. The bicycle coaster brake is a convenience in the operation of the apparatus as it allows freewheeling in the driving of the disk carrying the cameras, and the brake enables one to stop the rotation quickly.

To photograph a lightning flash, the whole apparatus is turned on the tripod head until the middle fixed camera is pointed in the probable direction of the expected flash. The shutters of all the cameras are opened and the moving cameras are rotated at a constant velocity.

It has been found that the shutters of the rotating cameras could be very conveniently and quickly opened by holding the finger near the top and front edge of the rotating cameras and allowing the shutter levers to strike the finger as they come around. The shutters are closed in the same way by reversing the direction of rotation. When a lightning flash or discharge from cloud to earth occurs, it is registered by some of the rotating cameras regardless of its position or direction from the apparatus, and it is also registered by one of the still cameras if it falls within an arc of 150 degrees in front of the apparatus. The camera shutters are left open and the disk with its cameras is rotated until three or four lightning flashes have occurred. The rotation is then stopped, the shutters are all closed, and the film in all the cameras is turned up for the next exposure. No difficulty has been experienced in sorting out the different component strokes that belong to a given flash, even when four or five flashes are registered on one exposure.

The photographs shown in Figs. 3 to 9 were taken of a lightning flash that occurred during a thunderstorm at Cleveland, Ohio, about 3:00 A.M., August 22, 1936. When these photographs were taken, the storm had passed over and was four or five miles distant towards the east. The apparatus was stationed on top of the physics building of Case School of Applied Science, but since a hill intervenes, the flash could not be photographed to its end at the ground; the lowest point which shows on the photograph is several hundred feet above the earth. The path of the flash photographed was probably one and one-quarter miles long.

Fig. 3 is a photograph taken by the middle fixed camera; it shows several discharges, but the one in which we are interested is the central flash coming down near the post supporting the guard rail. On the original film the branching is faint and extends downward. The photographs taken by the rotating cameras show the flash to have consisted of six component strokes, the whole flash occurring in 0.162 second.

Fig. 4 shows the first component stroke. It shows greater intensity at the bottom than at the top, perhaps due to better visibility near the earth. The width of the image of the stroke gives a probable duration of the stroke of about 0.00015 second; this cannot be determined with any degree of accuracy due to the halation of the photographic image. This stroke shows some branching, but the branches do not seem very intense in comparison with the main stroke; it is the only stroke that shows any marked branching. Perhaps of most significance is the fact that of all the components, this one alone was not preceded by a leader stroke.

Fig. 5 is a photograph showing the second component stroke which occurred 0.023 second after the first. The flash at the right, with its branch extending down and to the left, is a stray flash and is disregarded. This photograph shows the leader stroke and the main stroke

FIG. 2. Photograph taken by one of the fixed cameras. The central flash coming down near the post supporting the guard rail is under observation in this experiment; all the others are stray flashes.

clearly resolved. Their separation at the top gives a time interval of 0.00025 second from the starting of the leader stroke at the top until the return of the main stroke. The two strokes do not coincide at the bottom of the photograph since a hill intervenes, and the lowest point photographed is several hundred feet above the earth. Both leader stroke and main stroke show

FIG. 3. The first component of the flash, showing marked branching.

FIG. 4. The second component of the flash, showing a well-resolved leader stroke. Stroke shown at the right in this photograph is from a stray flash.

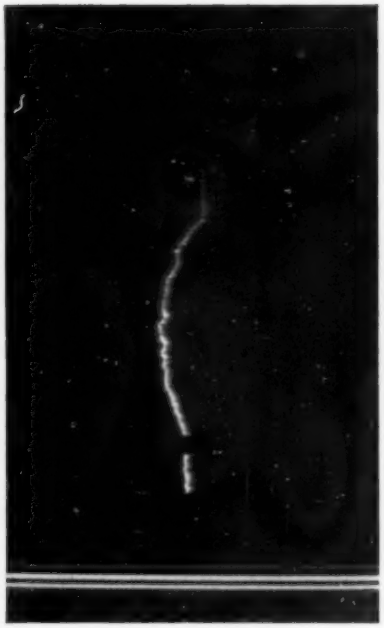

FIG. 5. The third component, showing a leader stroke.

one branch to the left about one-fourth the way up. The intensity of this stroke is considerably less than that of the first, though its duration is probably longer. The break in the image near the bottom is due to the corner post supporting the guard rail of the shelter house.

The third component stroke shown in Fig. 6 occurred 0.031 second after the second. Its leader stroke is not as intense as that in the second component stroke and the time interval between the leader stroke and the main stroke is less, being about 0.00016 second. This component shows no branching at all.

The fourth component stroke shown in Fig. 7 occurred 0.030 second after the third component. It shows a leader stroke somewhat more pronounced than that in the preceding stroke, and its separation from the main stroke gives a time interval of about 0.00020 second between its start and the return of the main stroke. The intensity of this main stroke is greater than that of the two strokes just preceding. The width of the stroke would indicate a duration of about 0.00020 second. This stroke shows no branching.

The fifth component stroke shown in Fig. 8 occurred 0.040 second after the fourth component. The separation of the leader stroke and the main stroke at the top gives an interval of 0.00020 second. The photograph shows no branching at all; it shows the greatest intensity of all the component strokes, also a greater duration than any of the previous strokes, about 0.00025 second.

The sixth and last component shown in Fig. 9 is really a double stroke with an interval of about 0.00075 second between the two, the first of the two occurring about 0.037 second after the fifth component. The first of this "doublet" shows a leader stroke very dimly, but none could be detected on the second. These two were very much less intense than the preceding components and the camera seems to have been slightly out of focus, making it difficult to measure the dispersion of the leader stroke accompanying the first, and to determine if any accompanied the second. The duration of the first was greatest of all the components, about 0.00030 second, while that of the second was about 0.00015 second.

If the paths of the component strokes are carefully examined and compared point by point, they are found to be identical in all. All of the component strokes show a leader stroke, except the first, with perhaps the exception of the second doublet in the sixth compo-

FIG. 6. The fourth component, showing a leader stroke.

FIG. 7. The fifth component, very intense, showing a leader stroke.

FIG. 8. The sixth component, a "doublet," the first of which shows a leader stroke very faintly; camera slightly out of focus.

nent. The first component stroke shows a great deal of branching, and the second shows a little branching, the leader stroke itself showing what appears to be a branch about one-fourth of its length from the bottom, the path of this branch being identical with the path of a branch of the first component. None of the subsequent strokes show any branching.

The apparatus was finished too late in the summer to observe many thunderstorms, but the experience gained in obtaining this one set of observations has suggested some improvements that are now being made. The focus of the cameras will be checked, and, if practicable, better lenses will be fitted to all the cameras.

Some distortion has been introduced by elevating the axes of the cameras; this causes some difficulty when the photographs made by the rotating cameras are compared with the photograph made by the still camera. In the improved apparatus, all cameras will be set level and a higher point for observations sought.

Several bright bands across the bottom of the pictures made by the rotating cameras are observed; they were made by the lights in the upper windows of a nearby hospital, and suggest another improvement. With the remodeled apparatus, having all the cameras set level, a small electric light bulb will be set some distance away (fifty feet or so) at the same height as the rotating cameras, and a second light bulb will be placed at the same height as the fixed cameras. When the shutters of the rotating cameras are opened, the lights will make bright lines across the middle of the photograph; the fixed cameras can be rotated once past the lights so that the lines will be registered on their photographs, also. These lines registered on both sets of photographs can then be used as base lines to compare the slopes of the leader stroke and the main stroke, as shown in the photographs taken by the rotating cameras, with the slope of the flash, as shown by the photographs taken by the fixed cameras. The differences in the slopes will be a function of the velocity of the discharge and the velocity of the rotating cameras. In this way the velocities of the leader strokes and main strokes can be determined independently of each other.

Plans are also being made to increase the gear ratio so that the cameras can be revolved at a higher velocity, thus obtaining a greater separation between the leader stroke and the main stroke. The centripetal reaction developed becomes a problem at the higher velocities of

rotation. This will be taken care of by placing an adjustable band around the fronts of the rotating cameras to hold them securely, and by placing glass plates in the backs of the cameras to support the film.

From this series of pictures and the photographs of other observers mentioned above, some inferences might be drawn. (1) It seems quite certain from the branching of the original stroke that the cloud is positive with respect to the earth in most cases, and certainly is in this series. (2) All the component strokes of the flash are preceded by a leader stroke except the first. (3) The direction of the leader stroke is from the cloud to the earth with a velocity that might vary from about 4×10^8 cm/sec. to about 12×10^8 cm/sec. (4) The main stroke that immediately follows the leader stroke travels in the opposite direction, that is, from the earth to the cloud with velocities that vary from about 15×10^8 cm/sec. to about 75×10^8 cm/sec. (5) It seems reasonable to conclude, since its velocity is so great, that the main stroke of each of the components is a flow of electrons from the earth to the cloud, forming a momentary current of vast proportions. (6) When the leader stroke passes from the cloud to the earth, immediately upon its arrival the main stroke leaves the earth for the cloud, following the identical path of the leader stroke but with a velocity four or five times greater. It is difficult to explain this action by assuming a reversal of so great a potential as exists between the earth and cloud in so short a time. The only alternative is to assume that the particles that constitute the leader stroke are opposite in sign to those of the main stroke, which are certainly electrons. It remains then that the leader stroke consists of positive particles, and they are traveling in the proper direction if the cloud is positive with respect to the earth, as inferred above. The leader stroke seems to prepare an ionized path, or at least a conducting path, which is followed by the main stroke.

When one attempts to apply the principles relating ionizing potentials, velocities, and masses of particles, to the above conditions, one finds that the velocities of all positive ions would be entirely too slow to be at all comparable to the velocities found in the leader stroke; a much smaller mass is required, a mass comparable to that of the electron, but the particles are moving in the wrong direction to be electrons. One could suggest that they are positrons, if their presence could be accounted for; they do not appear until after the first component stroke, so one could also suggest that they are formed by that first smashing stroke—the only stroke that shows branching—and are still present in its path when the first leader stroke which precedes the second component is formed.

The true explanation of these phenomena will doubtless lead to some very interesting facts.

Table of Characteristics of the Component Strokes.

Component Stroke	Intensity of the Stroke	Branching	Time Since Preceding Stroke	Leader Stroke	Time Interval at the Top Between Leader and Main Strokes
1	6	Marked	—	None	—
2	3	Slight	0.023 sec.	Yes	0.00025 sec.
3	2	None	0.031 "	Yes	0.00016 "
4	6	None	0.030 "	Yes	0.00020 "
5	10	None	0.040 "	Yes	0.00020 "
6	2–1	None	0.037 "	Yes	0.00025 "
			0.00077 "	?	?

The intensities were estimated roughly; the most intense component stroke was given an arbitrary value of 10. The double values given in the last row refer to the two components of the "doublet."

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The Liquid State

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I. Introduction

THE existence of three qualitatively different states of aggregation, the gaseous, the liquid and the solid, is shown by everyday experience. We know rather well the molecular characteristics of the two extreme states. In the gas, at least if its density is small, the molecules move mainly in straight lines with constant velocity, unaffected by the presence of the others, except during relatively short times, when they are in "collision." At a given moment, their positions are distributed irregularly. In the solid, or rather crystalline state, on the other hand, each molecule is constantly under the influence of its neighbors. As a consequence, the distribution is completely regular (i.e., at very low temperature and if we abstract of the zero point motion, the motion corresponding to half a quantum which persists even at absolute zero), the molecules are arranged in a geometrical space lattice; at higher temperatures, they oscillate around the lattice points.

But of the intermediate state, the liquid state, we know much less. Is it more alike to the gaseous state, as the theory of van der Waals implies, or to the crystalline state, as many modern investigators believe? Within the last years, a considerable interest in the theory of the liquid state has sprung up. The development of such a theory is the next great task which confronts the kinetic theory.

II. Some Properties of Liquids and Their Explanation

Let us first discuss roughly the outward characteristics of the liquid state. The most obvious one, used in elementary texts as definition, is that a liquid can take any form; it has no form elasticity, only friction.

Secondly, it is thermodynamically a distinct phase, with a sharp melting point, at which it is in equilibrium with the crystalline or solid phase.

Thirdly, it has generally smaller density than the solid at the melting point, a larger compressibility and expansion coefficient.

Fourthly, it has generally a higher specific heat.

In discussing these characteristics theoretically, we get into considerable trouble at the first point.

It is the resistance to shearing stress which keeps a solid in form. One finds, however, great difficulties in calculating this resistance to shearing stress even for crystals, where the theory works well in the explanation of other properties.

Brillouin[1, 2] considers first the crystal or liquid as built up of regular parallel planes, in which the atoms are situated in a checker board arrangement. There is a certain relative position of the subsequent planes giving minimum potential energy. If we have a force acting parallel to such a plane, trying to make it glide over the next lower one, i.e., if we have shearing stress, that plane would have to climb over a "potential hill," until, after moving over a distance equal to the period of the atomic arrangement in the plane, it would arrive again at a position with an energy equal to the minimum. If everything in each plane were completely rigid, the total amount of work would be zero. But as the atoms can be pushed out of their places slightly, elastic waves are set up, carrying energy away and so providing an energy loss, i.e., friction. But this process does not depend on temperature explicitly (a different effect, which does, has been calculated as unobservably small by Brillouin). Therefore, according to this theory, the decrease of viscosity with increasing temperature is due

to the fact that we work at constant pressure, the corresponding heat expansion diminishing the interaction of the planes.

A number of measurements of viscosities under high pressures have been made by Bridgman[3] and recently for oils by Dow.[4]

Bridgman himself has checked his figures with Brillouin's theory and Miss Carll has made some unpublished calculations for me. If one plots the viscosity at given temperatures against the volume instead of against the pressure, one gets curves which lie close together, but do not coincide, so that there is an explicit dependence on the temperature, although a large part of the decrease of viscosity is due to expansion.

Recently, Eyring[5] has developed a theory for the dependence of viscosity on T without taking into account the expansion.

Several years back, Frenkel,[2] Schottky and Wagner[6] have given an explanation for the electrolytic conduction in salt crystals at high temperatures, and Jost[6] has applied these ideas to diffusion. They assume that holes, unoccupied lattice places, form in the crystal in increasing number with increasing temperature, this number being given by a formula similar to that of evaporation. Without external field, such a hole would be filled with equal probability from the right or the left, a neighboring molecule slipping in and leaving a hole in its turn. But in the presence of an electric field there would be an excess of molecules coming from one side.

Similarly, Eyring calculates the number of holes formed in the liquid, $\sim\exp(-Q/RT)$, where Q is about the heat of evaporation. To fill a hole, either from left or right, a small potential hill has to be overcome (height ϵ/N), which happens $K\exp(-\epsilon/RT)$ times a second from left or right. But if there is a force f pushing to the right, the work necessary will be diminished for a molecule coming from the left by af, increased for one coming from the right against that force by that amount (a is a constant). Therefore, the excess of molecules going to the right under the influence of the force will be proportional to

$$K\,(\exp -(Q+\epsilon/RT))(af/RT)$$

or the viscosity proportional to $\exp(Q+\epsilon)/RT$.

In this theory, the expansion by heat is not taken explicitly into account, its effect is hidden in the value of Q.

Keeping the volume constant should in this theory not be expected to make the viscosity independent of T. The effect of pressure on the number of holes and therefore on the viscosity η should be

$$\ln(\eta/\eta_0)=1/RT\int p\,dV.$$

Although I have not actually checked this formula, I do not believe that it represents the facts.

We have next to discuss the meaning of the liquid as a phase.

In general, the equilibrium between two phases means equality of their free energies, or speaking in the terminology of statistical mechanics,[7] equality of the phasevolumina, each point weighted with the factor exp −energy/RT. If we restrict ourselves to temperatures high enough for the validity of classical statistics, we find

$$V_{1f}\exp(-\epsilon_1/RT)=V_{2f}\exp(-\epsilon_2/RT).$$

Here V_f means the average volume available for the motion of the center of a molecule, ϵ/N the lowest energy it can have in that phase. It follows immediately from this equation that in a phase which is formed under absorption of heat ($\epsilon_2>\epsilon_1$), the molecules must have more space available. The simplest case is that of sublimation. If Thomsen's principle, which makes the total energy content the deciding quantity, were valid, no vapor could exist, as it has always a higher energy content than the condensed phase. It does exist because the high improbability of having such a large energy is compensated by the large volume available for every molecule.

We conclude similarly that the free volume available in the liquid must be larger than in the solid. An empirical relation of de Forcrand says that the ratio

$$\text{heat of fusion/fusion temperature}=2\sim3.$$

That means

$$V_{lf}:V_{sf}=\exp(2\text{ to }3)/R$$
$$=\exp(1\text{ to }1.5)\text{ or }2.5\text{ to }4.$$

One can, therefore, understand the increase of the total volume at the melting point. However, this increase is larger than the increase in free volume. The formula for the free volume of the molecules in the solid, given by their vibration, is

$$V_{sf} = N(RT/(2\pi M\nu^2))^{\frac{3}{4}} = h^3(2\pi RM)^{-\frac{3}{2}}N^{-4}e\Theta^{-3}T^{\frac{3}{2}}.$$

Here Θ is the Debye temperature and e enters from averaging over ν^{-3}. However, the values of $V_{lf} - V_{sf}$ come out for Pb 0.1 cc, for Hg 0.03 cc while the experimental values $V_l - V_s$ are 0.6 and 0.5 cc. Therefore, a rearrangement must take place upon fusion which needs more space without giving so much more space to move, a kind of blocking effect (see Bernal, later).

If one calculates V_s from the entropy instead of from the free energy which means a different weighting, one has to multiply the theoretical values by $e^{\frac{3}{4}} = 4.5$ which brings the theoretical values closer to the volume increase on fusion.

In water, which gets denser on melting, the opposite takes place. Bernal and Fowler[8] have explained the arrangement of the water molecules in ice so that large holes occur inside a group of water molecules, which being triangles, form hollow tetrahedra by turning the H atoms towards each other. Upon melting, this arrangement breaks down and the holes disappear. What happens with iron, which also expands on freezing, is unknown.

One can understand qualitatively that the loser packing of the liquid gives higher compressibility.

The specific heat of the liquid can be divided into several parts.

1. $C_p - C_v$, which comes from the work done on account of the heat expansion.

2. C_v. In polyatomic molecules, this contains the internal specific heat, which is also present in probably the same amount in the gas.

The usually larger value of the specific heat of liquids as compared with solids is due to $(C_p - C_v)_l$ which, because of the higher expansion coefficient (which is again at least partly due to the higher compressibility) is considerable. Schulze has pointed out that it is 10 cal./mole degree for many organic liquids.[9]

C_v has been discussed for simple liquids mainly by Eucken[10] and his collaborators. At very low temperatures C_v is small (for the same reason as for solids), rises then to a maximum and falls again. This is interpreted by Eucken in this way: At very low temperatures the specific heat is due to oscillations similar to those in a solid. Their amplitude increases with the temperature but the deviations from the simple harmonic law become more and more important; finally a maximum elongation, defined by the distance between the molecules, is reached; with further increase of the temperature, the thermal motion approximates a zigzag translation and C_v drops to $3/2R$. Attempts to express these ideas in a formula giving more than qualitative agreement with the measurements have failed.

Brillouin[11] has called attention to the fact, that each R of the value $3R$ for C_v in a monatomic solid can be ascribed, respectively, to the longitudinal and the two differently polarized transversal elastic wave types which make up the heat motion in solids. Liquids can only propagate longitudinal waves, and Brillouin believes that the transversal waves go over into translational motions (eddy currents), having kinetic energy only and therefore specific heat $R/2$ instead of R. Therefore, he thinks that C_v for monatomic liquids should be R (longitudinal) $+ 2(R/2)$ (translational) $= 2R$. Eucken and Bartholomé[10] do not believe that to be in agreement with experiment.

For organic liquids, the internal specific heat is large and usually not determined accurately enough so that the part of C_v due to translation and rotation has not been calculated.

III. The Structure of the Liquid

As mentioned before, many investigators believe at present that the liquid state can better be described with the concepts developed for crystals than with those adapted for gases. That is due to the results obtained with the diffraction of x-rays by liquids.

To get definite results, it is, however, necessary to measure the intensities of the scattered x-rays up to large scattering angles. Formulae have been developed which permit the calculation of the density distribution around any given molecule from this intensity distribution. The interpretation of the results, however, is not simple. The first experiments showed rings which were ascribed to the existence of one

predominant distance between the molecules in the liquid.[12] Kratky[13] concluded from the measurements of Debye and Menke[14] on mercury, that the atoms in the liquid are arranged in densest packing with a certain range within which the position of each atom can vary.

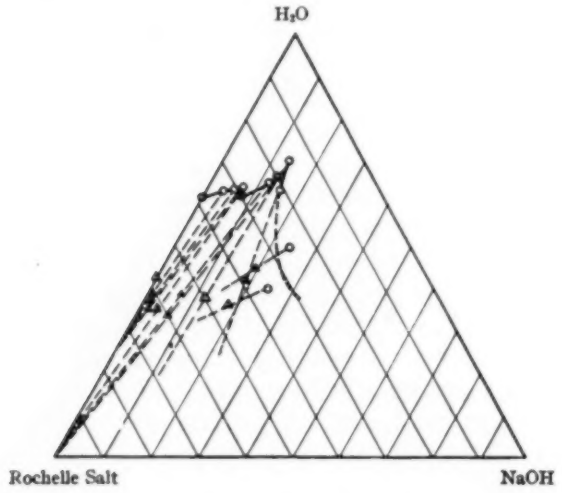

FIG. 1. Structure of crystal and of glass according to W. H. Zachariasen.

In the meantime Stewart[15] had found certain x-ray diffraction patterns in organic liquids, e.g. alcohols, from which he deduced the presence of small groups of molecules with similar orientation (cybotactic groups). We are going to discuss the problems of orientation afterwards. The idea of cybotactic groups has, however, been applied also to the position of molecules or atoms, leading to one of the two theories of the structure of liquids, the "microcrystalline" theory. The other, the "quasicrystalline" theory, has been particularly applied to the study of glasses, which are, since Tammann, considered as undercooled, highly viscous liquids.

The "microcrystalline" theory (Stewart-Randall)[15, 16] assumes that the structure of the liquid is essentially a regular space lattice, usually of the same type as the solid crystal, but in some cases, e.g. Bi, different. In general a liquid or glass, just as a metal, is polycrystalline, the groups, of about 10A dimension, slightly deformed. If one works carefully, a melt preserves characteristics (orientation as a whole or allotropic modification) of the crystal from which it was made. The difference between a highly viscous glass and a polycrystalline piece of solid is quantitative only (size of grains) and all intermediate states are possible.

A slightly different and an apparently more widely held view assumes small regions of crystalline structure imbedded in amorphous material (gas-like molecules, whatever that might mean). With increasing temperature the size of the crystalline groups decreases.

On the other hand, the "quasicrystalline" theory, sponsored by Zernike, Prins,[17, 18] Bernal and Fowler,[8] Warren[19] and Zachariasen,[20] assumes in a glass a rigid system of continuous networks, which have certain similarities with the geometrical lattice networks of the crystal, but deviate from it irregularly, although keeping the distances between neighboring particles about the same as in the crystal. In the liquid, this network varies with time. In this theory, there is no direct resemblance between the particular piece of crystal-lattice (as to orientation or allotropic modification, if this was not the most stable form) and the melt or glass formed from it, but the lattice of the latter is determined by the thermal situation and history.

To crystallize ("devitralize") a glass, bonds must be broken, there must be a sharp discontinuity between the two phases. This sharp discontinuity seems to me an advantage of the second theory because it gives two distinct thermodynamical phases. In addition most x-ray workers favor it, and Warren in particular has used it for the interpretation of many glasses.

On the other hand, there exist several experiments which seem to show a "memory" of the melt.

Othmer[21] has measured the speed of crystallization of molten salol. As is well known, the crystallization of an undercooled liquid is determined by the appearance of nuclei (Tammann) and the possibility of undercooling is generally assumed to be due to the delay in getting a sufficient number of molecules correctly oriented.* Othmer found that if he heated the melt only a few degrees above the melting point before cooling, more nuclei appeared than if the melt had been heated considerably. He interpreted this as a preservation of crystal nuclei in the melt just above the melting point.

* If that is true, it should be impossible to undercool monatomic melts, i.e., most metals.

Goetz[22] found upon melting a twin crystal of bismuth that the orientation of the crystal which reappeared upon cooling depended on that of the crystal which had been melted.

A particularly careful paper seems to be that of Donat and Stirstadt,[23] who used single crystal rods of bismuth. These rods were of two different crystallographic orientations. Fusion was brought about by regulating the current in an electric furnace surrounding a quartz tube, within which the rod reposed on a grove of shale. If the temperature was raised only 2° above the melting point and then allowed to drop slowly with complete avoidance of mechanical perturbations, the bismuth crystallized as single crystal with the orientation of the original rod. This was interpreted as a preservation of the lattice in the melt. If, however, the melt was even slightly shaken, it crystallized in the usual polycrystalline way; this is explained as due to the breaking of the lattice in the melt into small parts.

Valenkow and Poray-Koshitz,[24] whose presentation we have partly followed, investigate the x-ray diffraction pattern made by SiO_2 glass. They find a continuous series of diffuse patterns with increasing sharpness if they compare the following samples: glass made from α quartz, glass made from α crystobalite, a material made from silicagel which they interpret as a polycrystalline mixture of the two crystal forms crystobalite and tridymite, and finally small grained crystobalite. They ascribe to the first two glasses microcrystalline grains of 10–12A size, to the third material a size of 25A. The broader maximum for the first glass as compared to the second they explain by the breaking up of groups due to the transition quartz→crystobalite which occurs upon heating. They also interpret their experiments on sodium glasses according to the microcrystalline theory. Warren, on the other hand, finds a discontinuity in the x-ray pattern, when glass crystallizes.

If the above results and interpretations in favor of the microcrystalline theory are correct, they might explain the existence of the Smekal microstructure† of crystals as due to the solidification of liquids containing small cybotactic groups. The dimensions are right. On the other hand, one might attempt to explain all these results by impurities, like the oxide skins around metal grains, discovered by Tammann.[25] Experiments on the influence of the purity of material would be important.

Magat[26] favors the "quasicrystalline theory," because certain Raman bands which are ascribed to vibrations of the molecules as a whole in respect to each other, are shifted but not weakened upon melting, while the microcrystalline theory would require them to stay in place but lose intensity.

IV. Orientation

As mentioned above, the hypothesis of cybotactic groups originated in Stewart's observations on orientation of molecules in liquids. We must mention another phenomenon which shows that the molecules in a liquid do not rotate freely under certain circumstances. Debye had shown that for many substances with high dielectric constants, a large part of the dielectric polarization in an external electric field is due to an orientation of the molecules, which have permanent electric dipoles. If one determines a dipole moment for water vapor (by measuring its dielectric constant) and then calculates the dielectric constant for liquid water, one arrives at an absurd result. The actual value of the dielectric constant of water, high as it is, would lead to the conclusion that only about one-fifth of the molecules carry dipoles. Instead, Debye and Fowler have drawn attention to the fact that each molecule is strongly influenced by the field of its neighbors, which fluctuates, but is much higher than the smoothed out average field coming from the whole mass.

Debye[27] has in this way calculated the decrease in dielectric constant and Kerr effect and the lower degree of saturation under the action of strong external forces. In water, the inner field is of the order 6.10^7 volt/cm.

Fowler[28] assumes that the molecules are rotating freely if their kinetic energy is above a certain fraction of the potential energy of interaction with the field of the neighborhood; this field itself is assumed to be proportional to the number of nonrotating molecules. His

† There are many indications that crystals are often built up from minute blocks. There exist, however, artificial and natural crystals without block structure.

curves give qualitative but not numerical agreement with the dielectric behavior of polar liquids.

Frenkel[28] and his co-workers give a theory of the polarizibility of some polar solids by treating the rotating and the nonrotating molecules as separate phases.

V. Theories of the Liquid State

We come finally to the theoretical attempts to explain the liquid phase. The ideal of the theoretical physicist is to explain the properties of matter in bulk from those of the molecules. Therefore it should be possible to predict the existence of the liquid state, i.e., to close our eyes to the knowledge that it *does* exist and deduce, that it *should* exist. For the gas, in which the molecules are quite separate and in complete disorder, and for the crystal, where they are closely packed and in complete order, that is possible, but it has not yet been possible systematically to deduce the existence of all three states; perhaps the work of Mayer mentioned at the end shows promise in this direction. A previous attempt[29] to do it has failed, because the only model that could be calculated gave no distinct phases, but it showed that the condition for the existence of condensed phases, i.e., large masses as contrasted to medium sized complexes, is that the addition of one molecule to a large mass give a greater gain of free energy than addition to, say, a complex of three molecules.

The theories to be discussed start the approach either from the crystalline state (i.e., calculate the melting point) or from the gaseous state (i.e., calculate the vapor pressure).

Of the former, one of the oldest is the theory of Lindemann.[30] He considers the atoms or ions forming simple crystals as hard spheres executing harmonic vibrations, the amplitude of which increases with temperature. If the amplitude becomes so large that the particles collide with each other, fusion is supposed to occur. Lindemann finds the correct fusion point if he assumes for each different type of lattice a constant ratio between particle size and lattice constant. Of course, this theory says nothing about the liquid and therefore does not explain the phase equilibrium.

Braunbeck[31] has substituted for the simple quasielastic restoring force one which is periodic with the period of the lattice. A simple formula leads to two positions of equilibrium, which Braunbeck interprets as the crystalline and liquid state. It is possible to calculate the temperature where the two have equal free energy, i.e., the point of fusion. But the theory does not show why the second state is liquid and not another allotropic crystal.

Herzfeld and Goeppert Mayer[32] have made a systematic study of the equation of state of frozen argon in the hope of getting a clue to the process of fusion.

They assumed a van der Waals attraction Ar^{-6}, of the type introduced by London, and a repulsion $B \exp -r/\rho$, of the form found suitable by Born and Mayer[33] for alkali halides, the ions of which have rare gas outer shells. For ρ two values were tried, $\rho = 0.345$A which had been found suitable for the salts, and $\rho = 0.209$A for which there was a certain theoretical justification.[34] A and B were determined from the measured lattice constant and heat of sublimation. Then, the lattice energies, the elastic constants and from these the oscillation frequencies could be found as a function of the lattice distance. It was then possible to calculate the pressure p as a function of the lattice distance, i.e., the volume, and the temperature. The pressure is made up of three parts.

The variation of the lattice energy, i.e., potential energy, with volume, which means the purely elastic tension.

The variation of the zero-point energy with volume, i.e., the pressure resulting from the zero-point motion.

The thermal pressure resulting from the change of frequency with volume, which results in a change of the free, i.e., the available phase-volume with external volume. The result is shown in Figs. 2 and 3.

Now a simple consideration shows that

$$(\partial p/\partial v) < 0,$$

i.e., the pressure must decrease with increasing volume, otherwise the crystal will be unstable and explode, if perturbed. Therefore, the crystal cannot exist beyond the minimum of p. While the authors had originally hoped to get S-like curves as in the van der Waals theory, Fig. 4,

they saw this to be impossible and assumed the temperature, for which the instability occurs at zero pressure, to be the fusion point. Similar ideas had been expressed earlier by Raschevsky and Brillouin.[35] Of course, this also does not show how the liquid phase can be in equilibrium at this point with the solid.

Keesom and Simon[36] have found that helium is liquid at the absolute zero and solidifies only under pressure. That means that the zero-point pressure is larger than the elastic tension holding the crystal together. Herzfeld and Goeppert Mayer's calculations show this result, but are numerically far off. London[37] has given a theory which approximates the helium atoms by hard spheres. Simon thinks that the low temperature form of helium is a liquid with ordered arrangement.

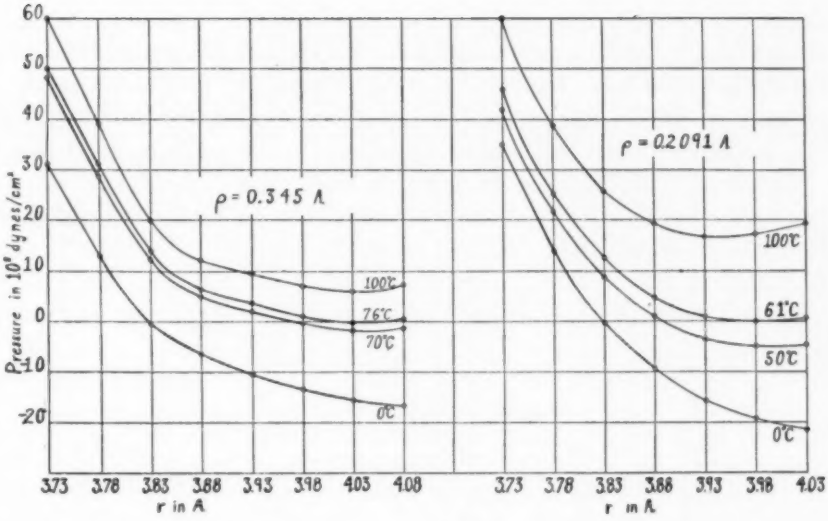

FIG. 2 (left). pr isotherms for argon. $\rho = 0.345$A, the value Born and Mayer found for the alkali-halides.
FIG. 3 (right). pr isotherms for argon. $\rho = 0.2091$A, the value found by Bleick and Mayer for He atoms.

Frenkel[38] emphasizes the gradual increase of irregularity in the crystal with increasing temperature, both as far as orientation (oscillation about directions slowly changing with time) and as far as position are concerned. He thinks that the characteristic feature of an amorphous substance (glass or liquid) is a lack of "long distance" regularity, while "short distance" regularity is preserved near the melting point and only lost at higher temperatures. A crystal, on the other hand, might have violent short distance irregularities (holes) near the melting point, while conserving long distance regularity. If one expands a crystal at low temperature by uniform negative pressure, the regular arrangement of the particles becomes unstable and so the long distance order might be lost, leading, according to Frenkel, to a continuous transition between crystalline and amorphous material at low temperatures.

I have tried in vain to get a theory of fusion by a consideration of the holes assumed to exist both in crystals and in liquids. Upon removal of one particle, i.e., upon making a hole in a crystal, the internal tension is relieved, the wall of the hole sinks in a little and an elastic field is set up in the surrounding material. If two holes are present, their elastic fields interact. If one treats the medium as continuous, the energy of interaction is found to be attractive and proportional to R^{-4}. I had hoped that one would find a temperature at which a state with few holes (the crystal) would be in equilibrium with one with many holes (the liquid), but it turned out that the number of holes increases monotonously with T.

Bernal[39] has considered an arrangement in which each particle has a given number of others at a distance r (first sphere of coordination). This distance is however not considered sharply fixed, but a Gaussian distribution around it is permitted. The number which defines the width of this distribution and the coordination number are determined so that the free energy is a minimum. Of course, both these values and therefore the configuration change with temperature. There is then a contribution of this change both to compressibility and to specific heat ("configurational compressibility and specific heat").

As to the sharp difference between crystal and liquid, Bernal believes it impossible to form a continuous transition between ordered and disordered states, at least in two and three dimensions. Trying it out for two dimensions, he

found it impossible to construct configurations, for which the relative root mean square deviation for the distance is between 0.05 and 0.2. Stating it differently, he characterizes the liquid state as one with points of abnormal coordination.

For the transition from the gaseous state, the classical investigations of van der Waals have to be mentioned first. They lead to the well-known equation of state; the S form of the pressure-volume curves, Fig. 4 permits the equilibrium

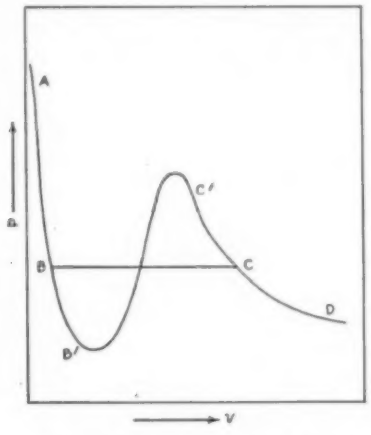

FIG. 4. p-v curve according to van der Waals.

between liquid and gas phase (the middle point corresponds to an unstable phase). But this theory would not lead one to expect the existence of a solid phase. In addition, the assumptions are too simple and cannot be reconciled with our present knowledge of molecular forces. Indeed, there is no quantitative aggreement with experiment.

Eyring[40] and his collaborator have modified the approach of van der Waals. Instead of subtracting the volume of the molecules, considered as hard spheres, or rather four times this volume, from the external volume to get the free volume

$$V_f = V - b$$

Eyring subtracts linear dimensions

$$V_f = B(V^{\frac{1}{3}} - d)^3.$$

B, d are constants. The dependence of the heat of evaporation, Q, on the volume is used in the form given by Hildebrand[41]

$$Q = A\,V^{-n}$$

and taken from his book. Then expansion coefficient and compressibility are calculated, usually in good agreement with experimental facts. The free volume of the liquids considered has been evaluated from the equation of state as 0.03 to 0.7 cm³ (it is much smaller for Hg), but this has not been checked against the vapor pressure.

Joseph E. Mayer[42] has gone back to the method of van der Waals, improved in two important respects. The molecules are not assumed hard spheres, and he starts out from the phase integral of the system, while van der Waals took the average attractive energy V^{-1}. This latter is approximately true for gases of very low density, because it means there that the fraction of the time one molecule is close to the other is inversely proportional to the total space available, and it is true again experimentally often for the liquid, but not at all in the intermediate states, where the formation of clusters occurs.

The method of the phase integral takes care of all that automatically, but the mathematics become very complicated. Mayer's method consists essentially of a classification of the groups of molecules which at a given moment are in interaction. He can then calculate the free energy and pressure of the system. At volumes, where part condensation occurs, the curve: pressure volume does not show the S form, but the form $ABCD$ (Fig. 4), because in a calculation which takes each possible state with its probability the unstable states of the curve $B'C'$ are too rare to count. The main remaining task is that of mathematical simplification and numerical evaluation.

In further investigations of J. E. Mayer and S. Harrison, as yet unpublished, there are indications that a transition to a third, the solid, state will appear, namely when groups which have such molecular interactions that the structure becomes stiff against shear become frequent.

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The research man is primarily interested in the unknown. . . . It is his restlessness in the face of the unknown, which Kipling calls "insatiable curiosity," that drives the research man to continual experiment—he needs the habit of questioning everything, of seeing the unknown in the familiar.

—LAWRENCE A. HAWKINS

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Flow Phenomena in Heavily Stressed Metals*

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Harvard University, Cambridge, Massachusetts

THE conventional experiment on material stressed beyond the elastic limit is self-terminated by rupture, as when the tensile strength of a rod is determined by stretching it, or its torsional strength by twisting it. The material separates and the ruptured pieces may not be rejoined. The result is that the distortions which may be studied are limited to comparatively small amounts, amounts so small that the original lattice structure, if the material is crystalline, must still play a dominant role. It is possible, however, so to arrange the geometrical configuration that plastic flow does not automatically terminate itself, but may continue indefinitely. Under these conditions a new domain of phenomena may be entered in which the only limit on the destruction of the crystal lattice is set by automatic recrystallization. Furthermore, the nature of the geometrical support is such that much higher stresses may be realized than under ordinary conditions. The maximum shearing stress realizable in ordinary metals is roughly one-half the ordinary tensile strength, which is comparatively low; by properly confining the material it is possible to realize shearing stresses ten or more times higher.

The experiments which form the basis of this paper were made by subjecting thin disks of material to heavy normal pressure between hardened steel surfaces which were simultaneously rotated in opposite directions about an axis normal to the plane of the disk, thus dragging the two faces of the disk circumferentially in opposite directions, and producing in the material of the disk slip on planes parallel to the faces. An account of these experiments has already been published elsewhere,[1] so that it will be sufficient to indicate here briefly the general nature of the apparatus and the method.

Fig. 1, which is a half scale drawing, shows the essential scheme of the apparatus. The disk of material *A* is compressed between a rectangular steel block *C*, called the "anvil," and a short boss on a cylindrical block of steel *B*, called the "piston." The anvil is rotated about the axis of the piston while the piston remains stationary. In order to avoid friction from end thrust the experiment is doubled by using a second disk and piston on the other side of the anvil, the anvil being rotated between the two stationary pistons. Pressure on the disks is produced by pushing the pistons together between the platens of a hydraulic press. The force required to produce rotation is measured as a function of the normal pressure and curves plotted of one against the other. The range of normal pressure consistently used in these measurements was 50,000 kg/cm². So high a value was made possible by the use of special steels and by the design, which is obviously such that the highly com-

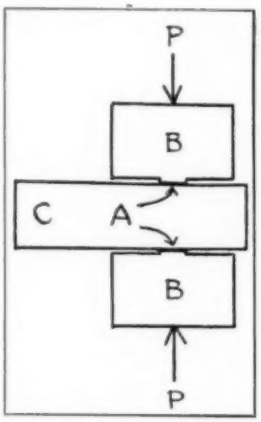

FIG. 1.

* Presented at the Symposium on Metals, Cambridge, Mass. January 28–30, 1937.

[1] P. W. Bridgman, Phys. Rev. **48**, 825–847 (1935); J. Geol. **44**, 653–669 (1936); Proc. Am. Acad. **71**, 387–460 (1937).

pressed bosses are supported by a large surrounding mass of steel in which the mean stress is much lower.

As normal pressure is increased beyond the yield point of the material of the disk, the material extrudes in the form of a sheet from between piston and anvil until the thickness has been so much reduced that further extrusion is prevented by the radial drag of the friction on the flat faces. It is obvious that if the friction is finite, any normal pressure whatever can be held in equilibrium if only the thickness becomes small enough. In these experiments the limiting thickness at 50,000 kg/cm^2 was between 0.002 and 0.010 cm, usually nearer the former than the latter. Detailed calculations, for which reference must be made to the other papers, show that in the majority of cases the effective friction which prevents further extrusion is confined to a relatively narrow annulus at the edge of the disk, so that the great central bulk of the material of the disk is in a state of approximately hydrostatic pressure so far as radial and normal components of stress are concerned, equal to the mean pressure exerted by the pistons. Superposed on this effective hydrostatic pressure is a shearing stress acting circumferentially in the planes of the faces.

In most cases the anvil was rotated manually, at convenient speeds up to a maximum of the order of one radian in 5 seconds from a minimum of perhaps one-tenth as much. The maximum speed was so low that a simple calculation shows the thermal effects are negligible. Rotation was almost always made back and forth through an angle of about 60°; the rotating force plotted against pressure was the mean of the force for the two directions of rotation. Readings were not made until an approximately steady state had been reached by a number of double rotations back and forth under half the maximum pressure. The shearing stress in the material during flow can be approximately calculated from the rotating force and the dimensions. It is this shearing stress, of course, which is significant rather than the rotating force.

The magnitude of the shearing distortion at the edge of the disk corresponding to a rotation of 60° in a disk 0.002 cm thick is 150 radians. Expressed in another way, one atomic plane is moved tangentially through 150 atomic diameters with respect to the next plane of atoms. The atomic displacement may be increased indefinitely by making the rotation continuous through many complete turns. This has been done in some experiments with no appreciable change in the character of the results.

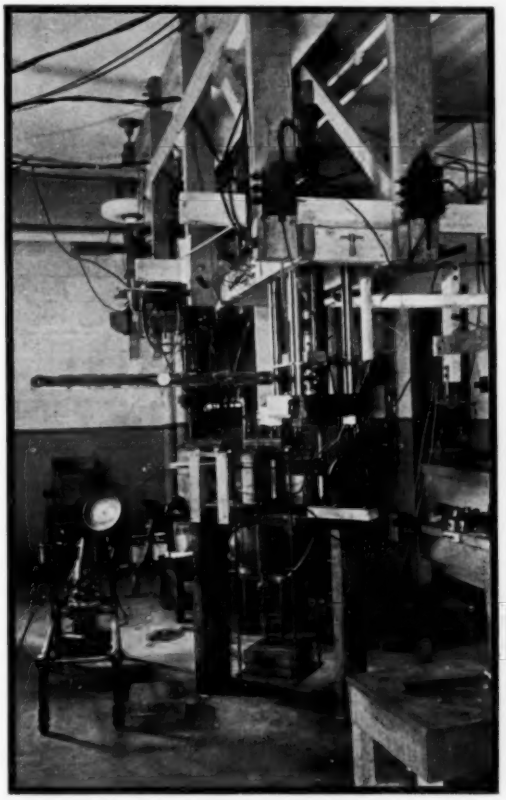

FIG. 2. View of general assembly. Hand pump for producing pressure at press. Dead weight gauge for accurately controlling pressure. Press with shearing apparatus in place, with rotating handle and gauge to produce and measure shearing stress.

The curves of shearing stress against mean pressure consist of two essentially different parts. The initial part of the curve corresponds to ordinary frictional slip at the surface between steel and disk, and the rotating force gives at once the usual coefficient of friction. Accompanying the tangential frictional drag on the surface of the disk there is, of course, an internal shearing stress within the disk on planes parallel to the faces, but in the initial stages this internal shearing stress is below the elastic limit of the material of the disk. As pressure on the faces increases, the frictional drag, and therefore the internal shearing stress, increases proportionally

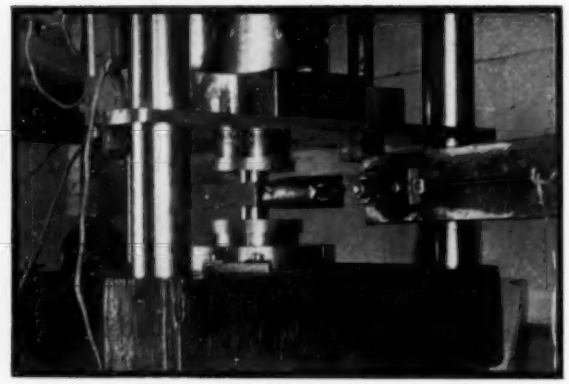

FIG. 3. Close up. Shearing apparatus in press with rotating handle attached.

to the pressure, if the coefficient of friction is constant, or more rapidly than the pressure if the coefficient of friction increases somewhat with pressure, as it usually does. Eventually a pressure will be reached at which the internal shearing stress reaches the plastic flow point, and from here on rotation involves an internal slip of the material of the disk on planes parallel to the faces, the faces themselves being frozen by the friction to the steel parts.

The change from surface slip to internal slip is reflected by a change in direction of the curve. If the shearing stress at plastic flow (which will be called hereafter simply the shearing "strength") were independent of mean hydrostatic pressure, then the curve of shearing stress would run horizontally beyond the point where internal slip begins. There are engineering experiments that indicate that to a first approximation in the range of engineering stresses the plastic flow stress is independent of normal pressure. Our first expectation might be, therefore, that the shearing stress curve would eventually turn and run horizontally. This, however, is by no means the case. There is in practically every case a "knee" in the curve marking the transition from surface slip to internal slip. Beyond the knee the curve of shearing strength continues to rise at a slower rate, and usually with a continually flattening tangent, but the curve is still far from horizontal. That is, shearing strength actually increases by rather large amounts in the pressure range up to 50,000 kg/cm²; doubtless the reason that this effect has hitherto been neglected is that the range of ordinary engineering stresses is not a large fraction of 50,000.

Typical shearing curves for two metals are shown in Figs. 4 and 5. Such curves have been determined for most of the elements which can be obtained in solid form, 57 in all, and for some 250 compounds. Reference must be made to other papers for the details. We shall here be concerned mostly with the metallic elements; I have as yet done practically no work on alloys.

The majority of shearing curves are smooth for their entire course, but a very considerable fraction, perhaps one-third, exhibit breaks in direction of one kind or another. Examples are shown in Figs. 6 and 7. These breaks in direction almost always mean a change in the lattice structure, that is, a polymorphic transition. Having once been detected from the shearing curve, the reality of the transition can usually be checked by other methods. Since my chief interest hitherto in the region of high pressures up to 50,000 kg/cm² has been in these polymorphic transitions, I have been using these shearing measurements rather in the spirit of a tool for the attack on the problem of polymorphism, rather than for their intrinsic interest. The following results have therefore been attained

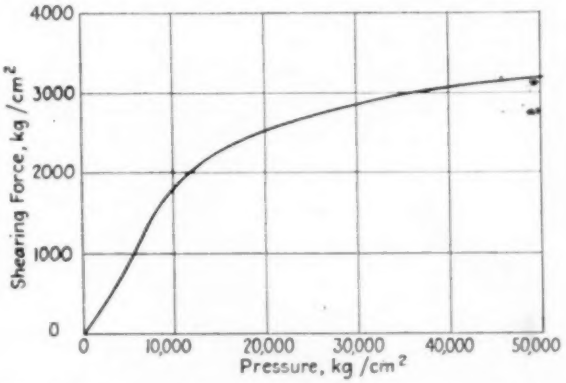

FIG. 4. Relation between shearing force and pressure for magnesium.

more or less incidentally, and there is room for much more systematic investigation of many points. I think, however, that enough information has been gathered with regard to the phenomenon of shearing itself under these conditions to justify a separate discussion.

In this paper I shall try to get somewhat further than in preceding papers in the attempt to understand the nature of the mechanism

effective in plastic flow. I shall not attempt to present a preliminary summary of the experimental facts, but rather develop the description of experimental details parallel with the picture of mechanism.

The big broad requirement that any mechanism has to meet is to explain the extreme qualitative difference between flow in a liquid and in a plastic solid. In a liquid the rate of flow is proportional to the shearing stress; in a solid, plastic flow does not occur at all until a critical shearing stress is reached, and once this stress has been reached flow varies from too slow to measure to too rapid to measure in a very narrow range of stress. This is the broad picture; second-order modifications of it will be described presently. The mechanism in liquid and solid must therefore be vitally different. The mechanism in a liquid is fairly well understood. It is a kinetic mechanism; shearing stress is the result of the transfer of a tangential component of momentum across the planes on which slip occurs. A solid surface moving tangentially with respect to the liquid is bombarded by molecules which have a net relative component of velocity tangent to the surface in virtue of the motion of the surface. Since this net relative component is proportional to the velocity, the momentum transfer, and so the force is also proportional to the velocity.

In order to see what may happen in a solid, consider in the first place the ideal case of a perfect lattice, with slip taking place along one of the crystallographic planes, as indicated in Fig. 8. Tangential slip of one plane past the next is at first resisted by ordinary elastic forces up to a maximum displacement of one-half atomic step. At this displacement the net tangential force vanishes by symmetry. During the final half of the displacement by one atomic step, considerations of symmetry show that the tangential force is exactly the reverse of that at the corresponding stage in the first half, so that if there is no permanent distortion in the lattice, no net work at all is required to displace the lattice by one atomic step. This means that if the lattice can once be got into a steady state of slip, it will continue permanently in that state of slip with no force to maintain it so. We have here a new state of matter, the "state of slip." In order to get it into the state of slip a force must be applied sufficient to overcome the maximum elastic force, but the force then drops back to zero.

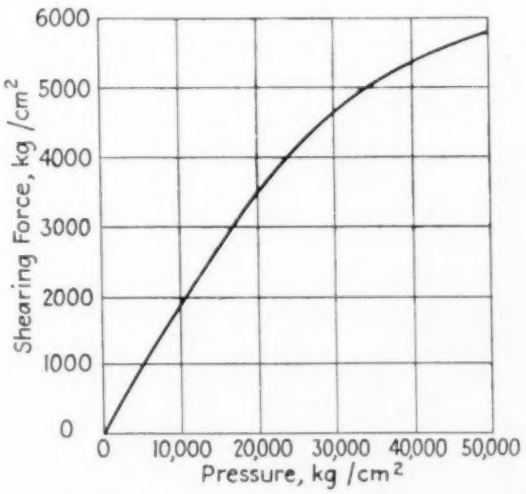

FIG. 5. Relation between shearing force and pressure for platinum.

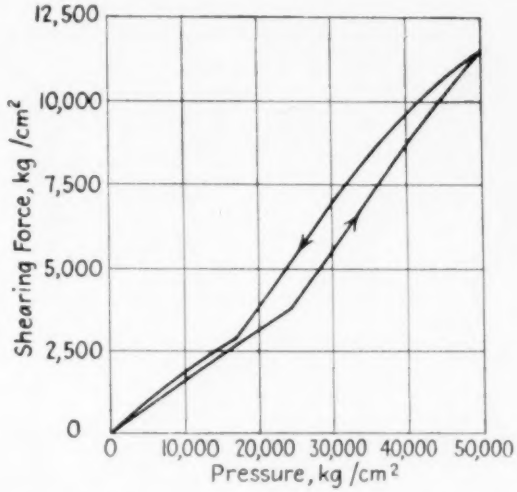

FIG. 6. Relation between shearing force and pressure for manganese.

This ideal state of slip of course does not occur; in understanding why it does not occur I think we find the clue to the phenomena of flow in solids. Flow is essentially an irreversible phenomenon; the energy input required to maintain flow is continually being dissipated. This demands some microscopic irreversibility in connection with the relative atomic displacements, and accordingly some modification of the picture above.

The most obvious modification is with respect to the perfection of the lattice. One would not expect the lattice to remain perfect under such drastic deformations as used in these experiments, and this is indeed the case. After the

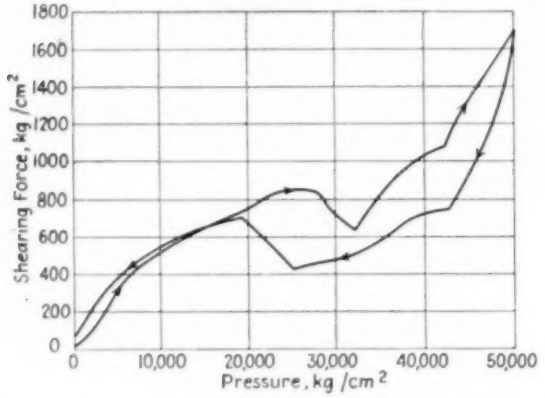

FIG. 7. Relation between shearing force and pressure for bismuth.

steady state has been reached any original gross crystal structure is dissipated into microscopic grains. If the disk is originally a single crystal with the slip planes parallel to the faces of the disk, zinc, for example, then shearing is at first so unbelievably easy as to almost raise the suspicion that the ideal state of slip has been attained. But as distortion proceeds the crystal structure gets more and more broken up, and the force climbs to continually higher values. The degree to which crystal structure persists in the final state depends on the specific metal. Thus in copper the crystal structure is reduced to such a degree of dispersion that only a single diffuse x-ray line can be detected in the final product, meaning a grain size probably less than 10A units on a side. In the lower melting metals like bismuth, on the other hand, the grain structure may be sufficiently large to give perfectly recognizable characteristic x-ray patterns. The lines, however, almost always become more diffuse. It can be stated, therefore, in many cases that the product is definitely not amorphous in spite of the severity of the deformation. The mere fact that polymorphic transitions occur in the disks while subjected to shear shows that in these cases the lattice must occur in blocks large enough to impart some of its characteristic properties. Imperfections in the lattice structure, however, drastic as they may be, cannot explain the irreversibility. They may, however, be the immediate occasion of the irreversibility. Two atomic slip planes in the final state must contain numerous atomic roughnesses, in the form of atoms projecting above their surroundings. When slip occurs, these will encounter other roughnesses, and will push them aside. If the amount of distortion necessary to allow the roughnesses to slip past each other is too great, the pushing aside will produce a permanent displacement of the projection. The result will be that the second half of a displacement through one atomic step will no longer be symmetric with respect to the first half, so that the work done during the first part, which would have been completely compensated if the system had remained elastic, is no longer compensated, and there will be an outstanding net expenditure of work for the complete atomic step. It is this outstanding net difference between the two halves of the displacement that determines the shearing strength, the shearing strength being the average force over the entire slip plane.

When the steady state is reached, as many new roughnesses are being created as are being

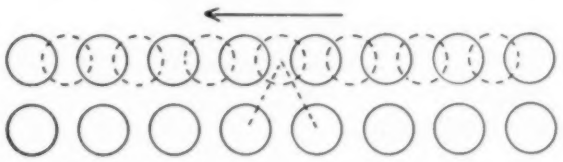

FIG. 8. Idealization of the arrangement of atoms in a lattice to illustrate the forces arising as a result of a slip along one of the crystallographic planes.

destroyed by the pushing aside of other roughnesses. These new roughnesses will carry on the function of the roughnesses destroyed. The new roughnesses will tend to be distributed at random, appearing as often in the first half as in the second half of the atomic step, whereas the roughness that disappears always disappears in the first half of the step. The net result is an outstanding contribution to the force in the direction resisting slip.

The net force, the resultant of the force in the two halves of an atomic step, is obviously to a first approximation determined by the geometry of the situation, and is independent of the speed of slip. Whatever part may be played by the natural atomic vibrations cannot depend to any

important extent on the speed of slip. For the highest speeds of slip reached in any of these experiments are very slow compared with the atomic vibrations, something of the order of 10^6 atomic vibrations occurring during one atomic step. We thus have an explanation of the most conspicuous difference between flow in a liquid and in a solid.

If the irreversible pushing aside of the roughnesses is followed by some sort of recovery process which proceeds at a speed comparable with the speed of atomic slip, then we may expect the force required to maintain continuous slip to vary with the speed of slip. Now although it is true that the force is nearly independent of speed for most metals, there are a number of cases in which there is very marked dependence of force on speed. The soft metals tin and lead show this in the most marked degree. In Fig. 9 is shown the logarithm of the speed of tin as a function of the force for two different pressures. It will be seen that the force increases by a factor of about ten for an increase in speed by 10,000-fold. This is still very far indeed from the behavior of a liquid but strikingly different from that of most metals. In the same diagram copper is shown for comparison to have an increase of force of about 30 percent for an increase of 10,000-fold in speed, whereas for mica the increase of force under the same conditions is inappreciable.

The variation of force with speed for tin and lead may be plausibly connected with their low melting points and capacity for recrystallization. Inelastic pushing aside of a roughness may be followed by a local recrystallization tending in some measure to restore the roughness to its initial position and so to return during the second half of the atomic step some of the compensating work which is lost when the roughness is permanently pushed aside. If the speed of slip is slower, recovery during a half-atomic step will be more complete, and so the net force required to maintain slip will be less. Since the observed force is the difference of two nearly equal terms, it is to be expected that a comparatively small change in one of the terms will produce a large change in the difference.

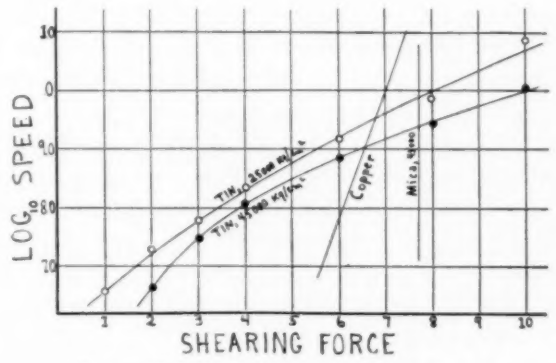

FIG. 9. Effect of speed on shearing force.

TABLE I. *Shearing strength under 50,000 kg/cm² compared with one-half tensile strength at atmospheric pressure.*

SUBSTANCE	SHEARING STRENGTH AT 50,000 kg/cm² (kg/cm²)	½ TENSILE STRENGTH AT ATMOS. PRESSURE (kg/cm²)	SUBSTANCE	SHEARING STRENGTH AT 50,000 kg/cm² (kg/cm²)	½ TENSILE STRENGTH AT ATMOS. PRESSURE (kg/cm²)
Al	3,200	300	Mo	12,100	3,500
Pb	650[1]	90	Ni	8,700	2,500
Cd	860[2]	325	Pd	5,600	1,050
Ca	1,800	250	Pt	5,800	950
Co	6,300	1,250	Ag	4,700	650
Fe	10,600	1,250	Tl	11,000	45
Au	4,500	700	W	12,700	7,500
Cu	4,900[3]	1,100	Zn	2,000	750–1,000
Mg	980[1]	1,000	Sn	770	125

[1] Atmos. 23,000. [2] Atmos. 10,000. [3] Atmos. 40,000.

At temperatures below the recrystallization range it is to be expected that the shearing strength, being determined purely by geometry, would be insensitive to temperature changes. This was found to be the case with copper; an increase of temperature from room temperature to 150°C resulted in only an unimportant decrease of shearing strength. In the case of liquids on the other hand viscosity is a very strong temperature function. Further measurements of the effects of temperature would be illuminating; I have not yet had a chance to make these.

Among the most important of the experimental results is the fact that the shearing strength increases by such a large factor at pressures of 50,000 kg/cm². Table I, reproduced from my *Physical Review* paper, compares the shearing strength at 50,000 for a number of metals with their shearing strength at atmospheric pressure, computed by taking half the ordinary tensile strength. Factors of increase up to as much as 10 occur. The very high increase for thallium is not significant in this connection, because under 50,000 thallium exists in a different polymorphic form from that at atmospheric pressure. This increase in shearing strength is probably in the

first instance merely a consequence of the fact that when the atoms are pushed closer together the atomic forces increase in intensity. The sort of average atomic force that is effective in shearing displacements is obviously a different sort of average from that which is effective in determining compressibility, for example, so that it is difficult to form any very quantitative idea of the magnitude to be expected for the pressure effect. It is to be remembered, however, that the net atomic forces effective in compressibility are attractive at atmospheric pressure at ordinary temperatures, and that these change to repulsive at pressures of the general order of 20,000 kg/cm², so that under 50,000 the net compressibility forces have become more strongly repulsive than they were initially attractive. Rather large changes in the shearing strength therefore do not seem surprising. Another factor tending to increase shearing strength at high pressures is that at high pressures the metal is farther from its melting point, so that any effects due to recrystallization would be expected to become less. Still another factor is that roughnesses which might slip past each other at large volumes will interfere at small volumes.

There are various transient phenomena connected with reaching a steady state. For instance, on reversing the direction of rotation the force does not usually at once reach its steady value, but passes through a consistent pattern of variation, usually simply falling from a higher initial value to a lower steady value, or climbing to a steady value from a lower initial value, or sometimes there is a more complicated pattern of oscillation. Sometimes as much as 20° of the total 60° of rotation is occupied in reaching a steady state, although usually much less is required, and there are substances which show no effect on reversal. Detailed explanation of these complications is beyond the reach of the simple picture just presented, but the picture does make it plausible to expect transient effects on reversing the direction of rotation. For the irreversible pushing aside of the atoms which constitute the roughnesses on the planes of principal slip demands slip by some secondary mechanism, either along channels or on other planes, and the ease of this secondary slip will depend on the orientation of the paths of slip with respect to the direction of motion. On first reversing the direction of motion there will therefore be a stage during which the secondary paths of slip are being reoriented, and during this stage of adjustment the force will not have its final value. The mere fact that there is an effect on reversing direction of motion demands the existence of some sort of flow structure different from anything that occurs while the material is in a state of ease at rest. This structure is not necessarily closely connected with the ordinary crystal structure, because these transient phenomena are found in glasses as well as in crystals.

The initial seasoning process required to get the virgin specimen into a steady state may continue for a very long time. Thus in the case of lead the state had not yet become entirely steady even after 100 double rotations through 60°, that is, after a displacement of one atomic plane tangentially with respect to the next through 30,000 atomic steps. It is evident that there is an enormous range of possibilities, with intermediate structures of all conceivable degrees of scale and complexity, between the macroscopic single crystal grain and material completely amorphous on the atomic scale. The extent of the hardening phenomena is evidence of the wealth of these possibilities.

A few metals and many of the nonmetals show, in addition to the phenomena so far discussed, another phenomenon of quite a different character. Instead of rotating smoothly, these substances rotate only with protest, usually noisy, of one sort or another. Some substances chatter, others squeak, others make a grinding noise, and one has been found to hiss. The most important of these variants of behavior is doubtless snapping. The rotation of many substances is interspersed with snapping at more or less regular intervals; the snapping is accompanied by more or less violent elastic reactions in the handle and other parts of the rotating mechanism and consequently a drop in the instantaneous rotating force. The simplest way of describing the behavior of the material of the disk is to say that it lets go to get a fresh hold. The actual angular displacement of the material of the disk while it is getting a fresh hold is usually very small. After it has got its fresh hold, the force climbs back to its former value, and the phenomenon presently

repeats itself. This phenomenon of snapping is in most cases superposed on the ordinary phenomena of plastic flow; in the intervals between snaps yield may be perfectly smooth, and there is usually no way of anticipating when the snap will occur. The angular interval between snaps often depends on the speed of rotation, the slower the rotation the greater the interval. In the case of some substances it is possible to rotate so slowly that the snapping entirely disappears, while with other substances the effect of varying speed through a wide range gives no indication that snapping would disappear even with much slower rotation. On the other hand there are a few substances, of which graphite at the highest pressures and quartz glass are examples, which do not yield at all by plastic flow, but rotation is accomplished only by a succession of jumps and snaps.

The metals are strikingly different as a class from the salts. Snapping is comparatively common among salts, but much rarer with the metals. The metallic elements which show it are: titanium, strontium (slight, at the highest pressures), cerium, arsenic, and osmium. Of these, titanium was known to have 5 percent impurity, arsenic is commonly regarded as a semi-metal although it is a rather good electrical conductor, and the osmium was an old lamp filament and was so excessively brittle that rather large impurities are to be suspected. There are 43 metallic elements that were found to shear perfectly smoothly over the entire range; this includes metals like beryllium, ordinarily very brittle, and metals with high melting points like zirconium, molybdenum, tantalum and tungsten.

A plausible explanation of this phenomenon of snapping or internal rupture may be given in terms of the picture already used. As slip proceeds between two layers of atoms the possibility of irreversible pushing aside of projecting atoms may tend to exhaust itself, the secondary paths of yield freezing up by a hardening process. The mutual yielding of projecting atoms will thus tend to become more elastic in character, the net force resisting flow will drop, and as long as the speed is maintained by elastic reaction of the large parts of the apparatus, the material will find itself in something suggesting our idealized state of slip. During the snapping there must be a rather large intensely localized generation of heat, which will undo the hardening effect and permit flow by the usual mechanism to start again after the force has dropped sufficiently. If the experiment is set up so that the force is maintained constant during the snapping, as by driving the rotating handle with a weight, then there is no chance for the material to "get a fresh hold," and the system runs away, once internal rupture has occurred. If the material is one in which recrystallization or some equivalent process of relaxation takes place with appreciable speed, then one would expect that snapping would become less frequent as the speed of slip becomes less, as it does in many substances, and would eventually disappear at such a speed that the natural relaxation can keep pace with the hardening. If the substance is so unyielding that insufficient internal irreversible adjustment is possible as, for example, quartz glass, then rotation can occur only with continuous internal rupture.

The difference between metals and other sorts of material with regard to snapping or internal rupture is doubtless to be explained in part by the fact that a great majority of the metals are cubic. Snapping is relatively less frequent in cubic substances than any others. A reason for this can be seen in the fact that every cubic crystal has at least three sets of planes of possible slip whereas in other crystal systems the number is less. In the hexagonal system, slip usually occurs only on the single basal plane. Of the five metals above listed as exhibiting internal rupture, three, Ti, As and Os, are already hexagonal. Of the two others, strontium and cerium, cerium certainly has a polymorphic transition near 13,000 kg/cm^2, and there is some evidence that strontium also has a transition at pressures below that at which internal rupture occurs. There is therefore no certain evidence that any cubic *metal* ever exhibits the phenomenon of internal rupture. On the other hand, internal rupture is of comparatively frequent occurrence among the hexagonal metals although somewhat less frequent relatively than among the hexagonal salts. It is tempting to see a correlation with the conductivity of the metal and the existence of free electrons. The unfilled energy bands of electrons may perhaps allow the structure to retain greater

possibilities of irreversible internal readjustment than would be possible if there were not this sort of a safety valve.

Finally, it seems to me that these experiments on unlimited plastic flow have something to say about the proper method of computing the strength of materials under more usual circumstances. It is well known that there are discrepancies between computed and observed strengths rising to factors of one hundred or one thousand fold, the computed value being too high. The conventional method that has been used to compute the strength, either in tension or in shear, is to allow the lattice to experience the corresponding distortion and calculate, in terms of the best knowledge available of the atomic forces, the restoring force thereby called into play. This restoring force is a function of the distortion; at first it increases with the distortion, but presently passes through a maximum. This maximum is now set equal to the strength, with discrepancies of the order suggested. This method of computing strength has seemed to me unsatisfactory;[2] it seems to me that strength is not a matter of the maximum force under a perfectly homogeneous distortion, but that it must involve considerations of stability and the conditions under which a microscopic rupture can extend itself if ever started.

The manner in which flow occurs in the experiments above has, I believe, definite bearing on this matter. If the torque on the rotating handle is slowly increased from zero, the first effect is elastic yield. This elastic yield increases regularly with increasing torque until by imperceptible degrees the stage of rotation begins, presently reaching rotation at constant speed under constant torque. At no time during the building up process does the torque drop back, but there is a monotonic rise. Under these conditions the shearing strength is merely the shearing force required to maintain constant flow. We have seen that flow at a uniform speed cannot be understood without understanding the mechanism by which energy is dissipated during this flow, and in fact in our picture it is the dissipative mechanism which determines the stress at which flow takes place. There is no hint at all of any such dissipative mechanism in the ordinary considerations by which strength is calculated; it seems to me that such a mechanism must play a decisive part in determining strength. This dissipative mechanism may evidently function in inducing instability.

The discrepancy between the strength as ordinarily calculated and the experimental value has been the occasion of much speculation. Various internal and external imperfections have been held to be responsible. Whatever the merits of these explanations under ordinary circumstances, it would seem that they cannot be especially pertinent under the conditions above. Internal flaws cannot persist on anything much more than an atomic scale, or amount to much more than irregularities in the geometrical arrangement of atoms squeezed into tight contact at pressures as high as these. The intimacy of internal contact is shown by the fact that self-welding is of almost universal occurrence; material originally finely powdered emerges after high pressure shearing consolidated into a homogeneous whole. Even less can surface imperfections play an essential part in flow under our conditions, because the lines of flow are curves closed within the material and never emerge at a free surface.

[2] P. W. Bridgman, Rev. Mod. Phys. **7**, 30 (1935).

The search for truth is in one way hard and in another easy, for it is evident that no one can master it fully nor miss it wholly. But each adds a little to our knowledge of Nature, and from all the facts assembled there arises a certain grandeur.

—ARISTOTLE

Edward Bausch—A Biography

By EVERETT W. MELSON

BORN at Rochester, N. Y., on September 26, 1854, Edward Bausch was introduced to the field of applied physics at a very early age. His home was literally a workshop. His father, John Jacob Bausch, had received the thorough optical shop training for which the German apprentice system was noted, before coming to this country in 1849. Germany was fast becoming the optical leader of the world. Fraunhofer's work in obtaining and testing ideal spherical surfaces, in improving the homogeneity of optical glass and exactly defining the refractive indices for certain well-chosen dark lines of the spectrum had laid the groundwork for the precise calculations of Ernst Abbe and for the development of the microscope. A new instrument was badly needed. Schleiden, the biologist, was unfolding the cellular theory and the microscope would permit him to prove his case by demonstration. Domrich was forging ahead in medical research and needed the microscope as an ally.

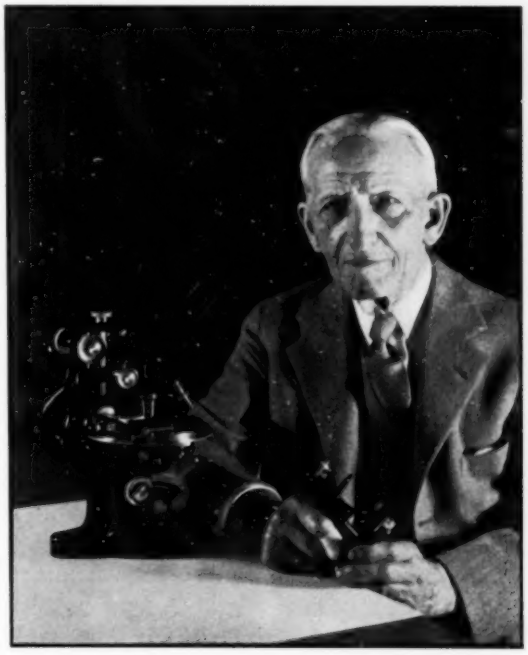

FIG. 1. Edward Bausch, chairman of the board, Bausch and Lomb Optical Company, with a microscope he built in 1872 and one of the latest research types.

In all this work John Jacob Bausch took considerable interest. He had a consuming ambition to increase his knowledge of optics and to make instruments of great precision. This ambition was early transmitted to Edward Bausch who constructed a microscope himself at the age of fourteen.

However, their little optical business which had been established in 1853 was forced to concentrate on the more profitable production of lenses and frames, although the word "profitable" is a great exaggeration. Frames at this time were made of horn, steel and leather and John J. Bausch was constantly experimenting in the hope of replacing these clumsy materials. A chance discovery of a piece of vulcanized rubber led him to make tests of this product. It could be molded to shape and it was light in weight. The new frames were successful.

One of Edward Bausch's earliest chores was to heat sheets of this rubber on the family cook stove until they were soft, then rush them to the woodshed where his father fed the sheets into a hand punch press operated by Henry Lomb. "Money was so scarce in those days," says Edward Bausch with a smile, "that a spoiled sheet of rubber could seriously embarrass the firm."

In the hours that he was free from school, Edward Bausch had absorbed much of his father's shop technique. But his father was determined that he should attend college before entering the business so in 1871 he entered Cornell University.

Rejoining his father and brothers in 1874, he was eager to begin the construction of microscopes. This desire was encouraged and plans were discussed with Zentmayer for sending him to Germany for special training. When this idea

was discarded, the firm employed Ernst Gundlach, an experienced German designer.

Work was begun on several microscope designs intended for the Philadelphia Centennial Exposition of 1876. Gundlach soon left the company and the brunt of the work fell on

FIG. 2. Old Bausch and Lomb plant of 1874.

Edward, William and Henry Bausch. When the exposition opened Edward Bausch was placed in charge of the exhibit and remained in Philadelphia three months, meeting scientists and inventors from all over the world. This exposition also provided an opportunity to observe foreign products which was valuable. The display of automatic machinery was, however, the greatest revelation, suggesting the further application of power to his own business which had been successfully inaugurated by his father when the first power lens grinding machine was introduced in 1861.

On his return to Rochester, a number of new microscope designs were begun and a new series of objectives computed. Anxious to introduce his new designs, Edward Bausch visited the principal educational institutions in the United States inviting laboratory workers to test the new products.

College laboratories did not exist in those days. Here and there, doctors and professors owned instruments and did much of their work at home. Mr. Bausch has a pleasant remembrance of Dr. Oliver Wendell Holmes, of the Harvard Medical School, who was one of the first to recognize the quality of the new American microscopes and to recommend them to students.

In 1878 a group of men interested in microscopy arranged to meet at Indianapolis where they formed the American Society of Microscopists, later known as the American Microscopical Society. Edward Bausch was a charter member. In 1884, the annual meeting was held in Rochester, with Dr. Dallinger, of the Royal Microscopical Society of England, noted for his work in deep sea biology, as the guest of honor. And it was at this meeting that the Spencer and Tolles Fund was created, the income from which is used to encourage unusual work.

Beginning in 1883, Edward Bausch's activity in the development of the microscope and other laboratory instruments is indicated by a succession of patents. In this year, he introduced the incandescent lamp, mounted in place of the mirror, on microscopes. In 1884 he designed a prism for the microscope tube in order to provide binocular vision. In 1885 he produced a new microtome with vastly improved performance. The invertible microscope followed in 1887 and in the same year came his well-known iris diaphragm shutter which made the snapshot camera the popular plaything that it is today.

It was through his various developments and inventions that Edward Bausch met George B. Selden who became his patent attorney. Selden later achieved fame as the inventor of the "horseless carriage." He it was who persuaded Edward Bausch to develop photographic lenses. Previously American made lenses had not met the competition from abroad. Edward Bausch's new lenses were of a quality comparable to the European product.

The improvement in photographic dry plates and the production of lenses of higher speed occasioned a demand for some method of exposure which should be faster and more perfectly controlled than was possible by manual dexterity. Edward Bausch's iris diaphragm shutter of the between-the-lens type solved the difficulty of rapid exposure. Replacing the clumsy and inefficient shutters previously in use it contributed greatly to the increasing popularity of photography. Cheaper types followed, all working at the diaphragm point of the lens, and were soon being exported to Europe.

On his first trip to Europe, in 1888, Mr. Bausch visited Baker, Beck, Swift, Crouch,

Powell and Leland Ross in England. On the continent he visited Reichert in Vienna, Goerz in Berlin, Leitz at Wetzlar and Zeiss at Jena. Dr. Roderick Zeiss showed him through the small plant that existed then. Returning, two years later, Mr. Bausch spent many months at Jena with Ernst Abbe. This contact finally led to the arrangement whereby an exchange of certain facilities was effected between the two companies. Dr. Hermann Kellner, whose early training had been with Zeiss, was brought over to establish a scientific bureau. It was realized that the structural elements of lenses must be expressed in absolute formulae and that thicknesses, diameters, and radii must be established by calculation. Aside from these purely numerical matters, technical methods must be devised for testing the accuracy of work done. Dr. W. B. Rayton, who was first assistant to Dr. Kellner, is now head of this greatly enlarged bureau.

It was evident to Edward Bausch that the market for microscopes was restricted by their cost. Each instrument was hand made, the work requiring skilled artisans. Europe thus had a competitive advantage because of lower wage scales. He had watched the introduction of automatic machinery and determined to apply some of the processes involved to the construction of microscopes, refusing to be discouraged by those who contended that the production of fine lenses was a matter of individual craftsmanship. One of his first devices to achieve his aims was the vertical arm grinding tool for microscope hemispheres in which a revolving spindle pivots in a receptacle below. The lens is mounted on either the upper or lower spindle with the opposite member fitted with a grinding or polishing tool of the proper curvature. This machinery was followed by numerous other inventions intended to provide automatically the eccentric motions required to grind or polish optical parts for many purposes. Millions of glass blanks mounted on pitch-blocks of the desired curvature are today ground and polished on such machines.

The production and distribution of microscopes at moderate prices for which Edward Bausch was largely responsible soon compelled the company to build complementary equipment such as cameras and projection apparatus.

FIG. 3. Edward Bausch with new contour measuring projector which accurately magnifies and measures the magnitude of error in machine tools and parts.

About 1893 the company had advanced steadily in the field of chemicals and laboratory apparatus. Beginning with the chemicals and stains used in microscopy, it had acquired a considerable business in chemical glassware. In 1904 a complete catalog of chemicals and chemical apparatus was issued. This was the first American catalog of its kind to use the metric system for both measurements and quantities. The continued growth of the optical industry made it advisable to dispose of the chemical business and in 1919 it was sold to the Will Corporation, of Rochester.

In the latter part of the nineteenth century, the United States Navy seeking a domestic source of supply for search-light mirrors, turned to Edward Bausch and his Rochester organization. These mirrors, ranging from 12 to 60 inches in diameter, had previously been imported from Europe. Bausch & Lomb began with the Mangin type and later substituted parabolic curves in making these enormous disks of perfectly tempered glass and of fine optical precision. The development of a process for silvering these huge mirrors to withstand the terrific heat was

in itself an achievement. When George N. Saegmuller joined Bausch & Lomb in 1905 he brought his vast experience as an instrument

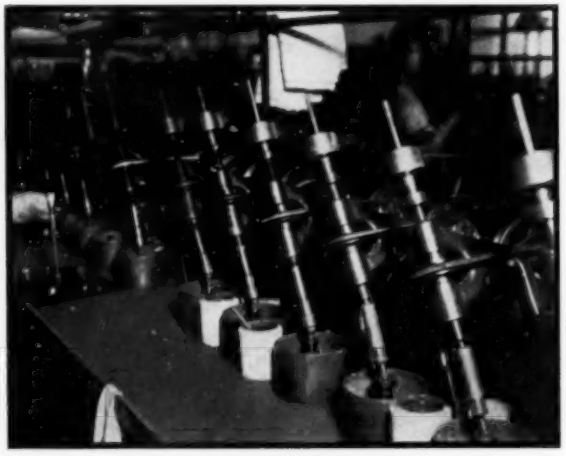

FIG. 4. Vertical arm grinding tool.

maker. His work as chief of the Instrument Division of the U. S. Coast Survey and as the designer of telescopic gunsights for the Navy added to the growing reliance on Bausch & Lomb for fire control instruments.

With the outbreak of the World War a domestic supply of optical glass became immediately necessary. Experiments in the making of this product, begun by William Bausch in 1912, were successful in 1915. The emergency is best described in the official report of the Ordnance Department, Document No. 2037, in which Colonel F. E. Wright, who was stationed at the Bausch & Lomb plant, describes the nature of the problem and the manner in which Edward Bausch and his associates met it.

Dr. Arthur L. Day, of the Geophysical Laboratories of the Carnegie Institution, who was in charge of the Government's efforts to provide optical glass for the armed forces related this incident of the war days. "Early in 1918 when it came to be realized by the War Industries Board that up to that time practically all the glass available to the government had come from the Bausch & Lomb Optical Company, and the other group set up to produce an equal share had been unsuccessful, I was sent to Rochester with instructions to wield a battle axe if necessary to increase the output to the limit. I entered Edward Bausch's office that morning with some misgivings. His cooperation up to that time had known no limit, and in point of fact he was fulfilling every requirement which had been laid upon him. My proposal was that he prepare again to double his output and that within thirty days. I shall never forget his reaction. He made no direct reply, but took with him a piece of chalk and led me into the glass plant. There he marked out on the floor with his own hand the vacant spaces which could be made to hold additional glass furnaces and gave orders for their immediate construction. No single question was raised. No moment lost. It was a spirit to overcome all obstacles and it did."

"So long as war stories are told," continued Dr. Day, "and the vital position of key industries for our defense are recognized, this country can never forget Edward Bausch."

The Bausch and Lomb families, under the inspiration of Edward Bausch, have extended the fine work of Captain Henry Lomb in the founding of the Mechanics Institute of Rochester,

FIG. 5. Air view of the present Bausch & Lomb plant.

an institution designed to offer training in all the mechanical arts. And the Bausch and Lomb Physics Building at the University of Rochester, which houses the Institute of Applied Optics originally sponsored by Bausch & Lomb and the Eastman Kodak Company, is an example of their generosity and their interest in improving the facilities for education in physical science.

Minute Nonferritic Particles in Steel*

By A. B. KINZEL †

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THE sources of minute nonferritic particles in steel are indeed numerous, as may be inferred from their composition. They may be broadly classified as austenitic particles, carbides, nitrides, intermetallic compounds and compounds of the oxide, sulphide and similar types. So little is known about minute austenitic particles in ferrite, and their existence within a single ferritic lattice is so problematic, that they will not be further considered in this discussion. Carbides, however, even in plain carbon steels may exist as discrete particles within the ferritic lattice, as shown by Bain and Heindelhofer.[1] Moreover, even when present at lattice boundaries they may exert a major influence on the physical and chemical properties of the steel. Intermetallic compounds and perhaps superstructures likewise probably exist within a single lattice in some of the complex alloy steels, although it is probable that in plain carbon steel this is not the case. Accordingly, they, too, will not be emphasized in this discussion. Nonmetallic matter is certainly present within the lattice as well as at the grain boundaries to such an extent that one is tempted to the generalization that this is true of all steel, and that steel may be classified as an emulsion. In the following, no attempt will be made to differentiate between the effect of minute particles of different character, but rather to note effects which might be produced by minute particles more or less independent of their chemical composition. It is, of course, recognized that the degree of the phenomena probably is affected by a change in character of the particles under consideration. Present knowledge of steel making reactions, together with the fact that relatively large amounts of refractory ladle lining are dissolved in the manufacture of any heat of steel, indicates the sources of nonmetallic matter in the liquid steel. Some of this material is eliminated in freezing, rising to form a relatively thin refractory slag cover on the top of the ingot, but much of it remains in the steel in the solidified state, either in the form of microscopic inclusions, submicroscopic inclusions, or in solid solution.

In the work carried out by Mr. Crafts and the writer an attempt was made to count the inclusions in a variety of steels, and the number of inclusions and their sizes were then plotted, grouped according to size.[2] It was found that as the size diminished, the number of inclusions increased in some exponential manner, so that the number of the smallest size which could be counted under the conditions obtained reached millions per square millimeter. It should be further noted that no observable change in the character or appearance of the inclusions took place on progressing from the larger to the smaller. In the larger sizes they could readily be identified as sulphides and silicates in many instances. In the smaller sizes this identification could be carried out only to a limited degree, but sufficiently well to rate it highly probable that all of the inclusions were of the same nonmetallic types. Moreover, the continuous increase in number as the size decreased argues against the possibility that after a certain small size was observed carbides or etching pits were

* Presented at the Symposium on Metals, Cambridge, Mass. January 28–30, 1937.

being counted. That the same situation exists with respect to carbides in steel is apparent. Although Bain and Heindelhofer did not count the precipitated carbides in their freshly quenched martensite, and although no counts seem to be available on carbides in troostite, qualitative inspection indicates the same type of exponential increase in number with decrease in size. It must be accepted, then, that steel as usually made contains an astronomical number of minute particles and the problem of the effect of these particles on the chemical and physical characteristics of the steel must be faced. That the solution of this problem logically requires the combined efforts of physicists and metallurgists will be generally granted.

The location of the minute particles is a matter of interest. Within the limits of accuracy afforded by the high sensitivity x-ray cameras there is no indication of lattice distortion in annealed steel, even though the millions of particles are present. This may be taken to mean that in such annealed steel the particles do not interfere with the unit lattice formation. However, in steels subjected to special low temperature heat treatments or tested at specific critical temperatures, either above or well below room temperature, there is ample evidence that embrittlement has occurred even though there is no evidence of lattice distortion. Various types of embrittlement are recognized, such as temper brittleness, strain-age embrittlement and low temperature embrittlement. A great amount of work has been done investigating each of these. Some of this work tends to prove that carbides are involved, some that nitrides are involved, and through it all one finds the general thought that probably oxides also are involved, although it has been difficult to establish this incontrovertibly. Moreover, some of the work indicates that carbides and nitrides may each be exclusively involved. This leads to the thought that any type of nonferritic matter suitably distributed may produce one or more of the phenomena. That the distribution of special intermetallic compounds may have a marked effect has been well demonstrated in the innumerable precipitation type alloys in which metallic compounds, carbides, or even single elements are intentionally distributed in such a fashion as to increase the hardness of the mass, and it is significant that in general this hardness is achieved with a disproportionately great loss of toughness. In other words, together with the precipitation type of hardening there is a strong tendency toward production of a brittle condition. Still other special phenomena are related to particle size and distribution. For example, the lack of resistance to corrosion or ready response to etching of plain carbon troostitic steels is a case in point. It is now recognized that troostitic steels are either a very fine pearlitic formation or very fine spheroidal carbide and ferrite formation, and that the response to chemical attack is at least partly correlated with the particle size of the spheroidal carbide or the fine lamellae of the pearlite.

The above cited phenomena show that the fine particles have a marked effect on both the physical and chemical properties, and it is significant that in many of these instances the phenomena are qualitatively independent of the nature of the particle. For example, aluminum may be hardened with a variety of precipitates. Tungsten, vanadium and chromium carbide type troostites are attacked about as readily as the iron carbide type. This indicates that the effect of composition alone on the differential electric potential is not sufficient to account for all of the manifestations of the phenomena. Another factor must be involved. It is interesting to examine the hypothesis that this other factor is stress corresponding to internal strain produced by the presence of minute particles. Most of

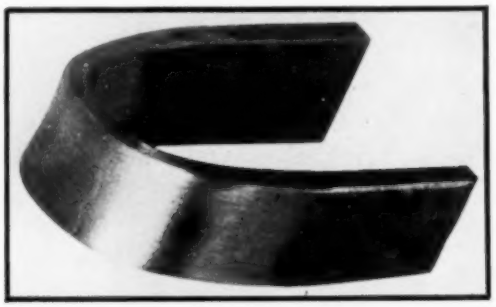

FIG. 1. An example of the excellent ductility imparted to this welded bend specimen of 25 percent chromium steel by the addition of 0.20 percent nitrogen. Do nitride inclusions acting as crystal nuclei produce grain refinement and resultant ductility? If this is true, some types of fine inclusions can be beneficial.

the particles in steel as well as in other metals show differential solubility increasing with temperature, and in certain unstable conditions the

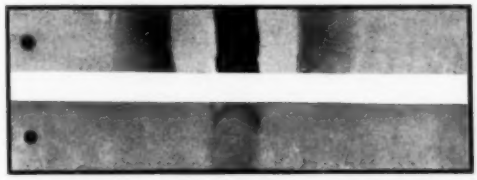

FIG. 2. (a) Intergranular corrosion alongside a weld in a specimen of 18–8 chromium-nickel stainless steel that has been exposed to the action of boiling acidified copper sulphate. Is susceptibility to this type of corrosion due to the stresses of precipitated carbides? (b) Supporting such a hypothesis is the fact that this columbium-bearing 18–8 weld specimen did not become corroded when similarly exposed. Presumably, the columbium prevents the precipitation of stress-forming carbide inclusions.

saturated material may be precipitated even at room temperature, and perhaps at very low temperatures.

Consider the case of low temperature brittleness. Brittleness may be defined as lack of plastic deformation under stress approaching the maximum strength of the material before rupture. Plastic deformation of steel presumably occurs by slip on crystal planes, with self-strengthening of each plane in the act of slipping. Lack of plasticity is then due either to prevention of slip or resistance to slip increased to a stress level at which the strengthening effect becomes inoperative or insufficient. Slip may be prevented by the presence of keying particles, according to the theory of Jeffries and Archer, but it may also be prevented by the presence of stresses at right angles to the externally applied stress. Considering the concept that, except for a minute volume change, deformation is impossible in a member subjected to equalized three-dimensional tension, the possibility of eliminating slip by means of stress in three dimensions is readily evident. Moreover, according to Poisson's ratio the stresses existing at right angles to the applied stress need only be approximately one-third of the applied stress in order to effectively prevent deformation. If it is assumed that with lowering temperature, differential contraction between minute particles of nonferritic material and the ferritic matrix of the steel produces hoop tension in the ferritic matrix surrounding the particle, there is set up a condition of internal stress microscopic or even submicroscopic in character, which may well be sufficient to prevent general deformation. In other words, the existence of internal stress produced by the presence of minute particles may well account for low temperature brittleness. Little information regarding this hypothesis has been gleaned from the industrial solutions of the problem based on alloying additions.

The hypothesis is offered not as a working theory but rather as a query for consideration of the physicist, and is illustrative of the type of problem posed by the known existence of minute particles.

Again consider the matter of strain-age embrittlement. Straining increases precipitation velocity and presumably results in formation of minute particles on subsequent aging. It is plausible to assume that such freshly precipitated minute particles formed at room temperature result in highly local internal stresses in the material which again restrict deformation in any direction and are responsible for brittleness. Elimination of this phenomenon in steel by the addition of small amounts of "deoxidizing" elements yields some clue as to its causes. This is another phase of the internal stress problem which the metallurgist offers the physicist.

The matter of temper brittleness may well be simply another evidence of the general phenomenon and a hypothesis similar to that offered for low temperature brittleness or the strain-aging phenomenon is obvious and presents another phase of the problem to which the physicist might well devote himself. The effect of various alloying elements on the rate and degree of this phenomenon fail to lead to any satisfactory explanation.

The foregoing arguments have dealt with the possible effect of minute particles on the physical properties, but it also is to be supposed that they play a major role in determining the chemical properties, particularly corrosion resistance. The etching of troostite has already been mentioned and this may well be extended to the phenomenon of intergranular corrosion in austenitic steels. When subjected to specific heat treatment such steels exhibit precipitation at the grain boundaries, probably involving both microscopic

and submicroscopic particles. One much quoted theory holds that such particles are carbides rich in chromium and that correlative to this chromium enrichment of the carbide particles impoverishment of chromium occurs in the surrounding mass with consequent susceptibility to chemical attack. It may well be, as the writer has previously pointed out,[3] that chromium impoverishment is entirely unnecessary to account for the corrosion phenomenon. It is difficult to believe that chromium atoms can migrate to form a carbide, but cannot migrate to produce relative homogeneity. This is particularly true when it is recognized that the phenomenon takes place almost as readily in 25 percent chromium as in 18 percent chromium austenitic steels and that presumably only 12 percent chromium is necessary for relative freedom from the type of chemical attack in question. It would seem to be more plausible to simply extend the phenomenon occurring in troosite and assume that internal stresses about the carbides result in the increased chemical attack. It is interesting to note in this connection that the very satisfactory practical solution of the problem afforded by the addition of amounts of columbium or titanium in suitable relation to the carbon content does not offer any positive clue as to its nature, other than to emphasize the important role of carbon with respect to the precipitate. That cold work, particularly if it is local in character, decreases chemical resistance is generally recognized and we may well assume that intergranular corrosion in austenitic steel is simply a special case of this phenomenon. Analogous phenomena in ferritic chromium steels have been discussed by MacQuigg.[4]

In ordinary carbon steel, experiments have been carried out at the Union Carbide and Carbon Research Laboratories in which a drop of saline solution containing an indicator has been placed on a freshly prepared surface and a stopwatch used to determine when the amount of iron necessary to affect the indicator has been dissolved. The same piece of iron was then placed in a tensile testing machine and stress applied well below the elastic limit. As the stress was increased the time necessary for the indicator to react was decreased in a continuous manner within the limits of error of the experiment. It is true that these limits were sufficiently wide and the experiments sufficiently difficult to duplicate so that the results have never been published. They are, however, sufficient to be positive proof that so-called elastically strained material is attacked more readily by a chemical medium than unstrained material and that the rate of attack increases as some function of the degree of strain.

The writer holds no brief for the hypotheses above suggested, but the effect of internal stress on the physical and chemical properties and the possibility of the production of such internal stress by minute nonferritic particles in steel cannot be dismissed lightly. The hypotheses taken in their entirety offer a correlated explanation of many diverse phenomena in steel and were they amplified and substantiated by the work of the physicist they would offer a working theory of real value to metallurgists. In their present state the hypotheses involve many assumptions, are accompanied by insufficient experimental data and are subject to much controversial argument. They are set forth here primarily as a challenge to the physicist.

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2. Kinzel and Crafts, Trans. Iron and Steel Division. A. I. M. M. E. p. 151 (1931).
3. Discussion by author of Bain and Aborn paper. A. S. S. T. **18**, 875 (1930).
4. MacQuigg, *Book of Stainless Steels*, second edition, p. 363.

Here and There

¶ The John Simon Guggenheim Memorial Foundation has announced the following fellowship awards in physics:

Dr. Ronold W. P. King, assistant professor of physics, Lafayette College, experimental and theoretical study of application of Maxwell field equations to circuit problems at ultra-high-frequencies.

Dr. Hans Mueller, associate professor of physics, Massachusetts Institute of Technology, to study structure and properties of liquids.

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Coffin Fellowship Awards

¶ Established by General Electric in 1922 to honor its retiring president and founder, Charles A. Coffin, these fellowships, totaling $5000 annually, are awarded yearly to graduates of colleges in the United States who have shown by the character of their work that they could with advantage undertake or continue research work in educational institutions either in this country or abroad. Since 1923, approximately 100 students have been enabled by these fellowships to accomplish important studies. Among their ranks is the 1936 Nobel prize winner in physics, Carl Anderson, who won an award in 1927.

Of the 1937–8 fellowships, two are renewals. Julian Schwinger at Columbia, who is studying the scattering of neutrons by deuterons, and Harold G. Vogt at Harvard, who is investigating the nature of the neutron, also won awards last year.

The six other 1937–8 winners of the Coffin Fellowships are pursuing a varied group of subjects. Joseph R. Dietrich, of the College of William and Mary, will study the propagation of potential in discharge tubes. He will carry out this work at the University of Virginia.

Henry P. George, of Lehigh University, will engage in research work at Carnegie Institute of Technology and his problem will pertain to the rate of diffusion at grain boundaries.

Donald L. Herr, of the University of Pennsylvania, will remain there studying oscillation in nonlinear circuits.

Two of the winners will study at the Massachusetts Institute of Technology. Nathaniel I. Korman, of Worcester Polytechnic Institute, will do research measurements at ultra-high-frequencies; and Stuart T. Martin, Jr., already at M.I.T., will observe the thermionic emission and absorption properties of tungsten crystals.

Richard W. Mattoon, of Antioch College, will study the deposition of successive monomolecular films onto solids. This work will be done at the University of Chicago.

The minimum amount awarded in a Coffin Fellowship is $500, and frequently a student obtains a larger amount as his studies demand. Since 1923, when the fellowships were first given, approximately $75,000 has been paid to their holders.

¶ At the time of the installation of a chapter of Sigma Xi at George Washington University, the following Doctorates of Science were conferred:

Charles Greeley Abbot: persistent and courageous investigator in the field of astrophysics, in whom scientific thinking and religious reflections are not separated; secretary of the Smithsonian Institution.

Paul Bartsch: eager scientist; teacher; quick to appreciate human values; who, for years, has devotedly served in the George Washington University.

William Bowie: graduate of Trinity College (Connecticut); cheerful colleague and tried friend of those who seek for truth; to whom long experience in scientific endeavor has brought recognized leadership.

Lyman James Briggs: sincere scholar and worthy public servant, in whom firmness of conviction and tolerance toward the beliefs of others go hand in hand; chosen to direct the National Bureau of Standards.

George Braxton Pegram: son of the South; well-known investigator and expounder of physical sciences; worthy servant of Columbia University; acting-president of the Society of the Sigma Xi.

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¶ In planning for the June meeting of the American Physical Society June 22–23 in Madison, the local committee has followed the practice of arranging a somewhat more extensive entertainment program for physicists attending the summer meeting, and their guests, than is usual for other meetings during the year.

A tour through the greatly enlarged new United States Forest Products Laboratory is being arranged. In addition to a wide range of items of technical interest the laboratory contains many displays and examples of wood processes and properties of general interest. Madison, located on an isthmus in a chain of lakes, is ideally situated for summer recreational activities, and facilities for a variety of land and water sports will be available. Trips to points of scenic interest are in prospect.

Arrangements are being made to house visitors in the university dormitories at $1.50 a night. Because of the noncommercial nature of these arrangements, it is imperative that reservations be made early. Communications with regard to housing may be addressed to the chairman of the Physics Department, University of Wisconsin.

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¶ Dr. A. Nadai sailed April 10th to attend the International Congress for Testing Materials in London. He plans to visit Germany before returning to this country.

Surface Chemistry

¶ At the Spring meeting of the American Chemical Society at Chapel Hill, N. C., April 12 to 15, a symposium was held on the general topic of "Surface Chemistry." Ten invited papers were presented which dealt with some aspect of the formation and properties of gaseous, liquid, and solid films on both liquids and solids. Attention was centered particularly, however, on work connected with adsorption and catalysis in gas-solid systems. The papers dealing with phases of the subject that are probably closely related to the field of applied physics were the following:

Irving Langmuir of the General Electric Company described some of the very interesting results that he and his colleague V. J. Schaefer have been obtaining in their study of the properties of monomolecular films of stearic acid on water, and of these same films after they have been transferred to suitable glass plates or other solids. The influence of *p*H and of the presence of salts of Cu, Zn, Ag, Pb, Mg, Ca, Ba, K, Fe, Al, and Sn on the properties of the films was especially discussed, it being pointed out that even minute amounts of salts of these metals can effect marked changes in the properties of the stearic acid films.

Otto Beeck of the Shell Development Corporation, pointed out some of the striking results that can be obtained by using a molecular beam technique in measuring the catalytic decomposition of hydrocarbons on metallic surfaces. He has succeeded in demonstrating that traces of some polar molecules such as H_2O or H_2S must be present before a platinum disk heated to 1300°C or so will dehydrogenate saturated hydrocarbon molecules impinging on the metal surface.

P. H. Emmett and Stephen Brunauer [Bureau of Chemistry & Soils, U.S.D.A.] described the details of the method that they are using for measuring the surface areas of iron synthetic ammonia catalysts. The method comprises the determination of the physical adsorption isotherms of various gases close to their boiling points and the selection of the point on each of the isotherms believed to correspond to the completion of a monomolecular layer. The experimental work has definitely revealed the coverage of a large fraction of the surface of iron catalysts by promoters even though only 1 or 2 percent of the latter might be present in the sample as a whole, and gives promise of being widely applicable to the measurement of the surface areas of various porous finely divided solid substances.

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Mass-Spectrograph Applications

¶ A. Keith Brewer of the Bureau of Chemistry & Soils, discussed the use of the mass spectrograph in determining isotope compositions and atomic weights, at the Chapel Hill meeting of the American Chemical Society. The mass spectrograph described was of the Dempster type with a special constant velocity source available for the analysis of the alkali and alkaline earth metals. The advantages attributed to this physical method of analysis are that absolute atomic weights can be determined in a few hours from minute quantities of unpurified materials with an accuracy comparable with chemical methods, while comparative atomic weight measurements can be made with an accuracy appreciably greater than can be obtained by the best chemical technique.

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British Conference on Industrial Physics at Birmingham

¶ The British Institute of Physics held its second conference on Industrial Physics at Birmingham, March 18–20. The demand for this and other conferences arose out of the rapid development of industrial applications of physics to industry in recent years and the accompanying desire for an interchange of ideas. The special subject for this conference was Optical Devices in Research and Industry.

The sessions were held in the University of Birmingham. The conference was formally opened by Mr. Walter Barrow, pro-chancellor of the University, and was presided over by the president of the institute, Professor A. Fowler. Following the established practice of the Institute, the lectures were all informal in character and were followed by discussions. Neither the lectures nor the subsequent discussions will be published, except the presidential address, which will appear in an early number of the *Journal of Scientific Instruments*. The title of the presidential address was "Spectroscopy in Industry."

The other lectures were: "Colorimetry, Spectrophotometry and the Inspection of Manufactured Products for 'Appearance,'" by Mr. R. Donaldson, of the National Physical Laboratory; "The Application of Electron Diffraction to Industrial Problems," by Professor G. I. Finch, of the Imperial College of Science and Technology; "Industrial Uses of Photo-Cells," by Mr. A. L. Whiteley, of the British Thomson-Houston Co., Ltd.; "Optical Gauges for Metrology and Engineering," by Mr. F. H. Rolt, of the National Physical Laboratory; "Polarimeters, Saccharimeters and Refractometers in Sugar, Jam-Boiling and Other Industries," by Mr. L. Eynon, of Messrs. Eynon and Lane, official analysts to the Sugar Association of London.

The attendance at each of the lectures was excellent, averaging 325. Both the lecturers and those who took part in the subsequent lively discussions dealt with recent industrial applications of various optical and allied devices and the associated problems, rather than with the technical details and underlying principles of the devices themselves.

Twenty-three firms and research organizations were represented at an exhibition of apparatus, instruments and books cognate to the subject of the conference, which was held in the physics laboratories of the university. The Government's recognition of the importance of physics to industry was demonstrated by several exhibits contributed by the National Physical Laboratory and the Post Office Engineering Research Station. A special section of the exhibition was devoted to optical experiments of general interest, including many ingenious applications of photocells. The object of the whole exhibition was to demonstrate the existence of apparatus and instruments designed on well-known physical principles for use in the workshop and factory. A limited number of copies of the catalog of the exhibition is still available from the Institute of Physics, London, S. W. 7 (9*d*. postpaid). It is estimated that about 2500 people visited the exhibition during the three days that it was open.

¶ The *News Bulletin* of the Institute of International Education announces that in honor of the three hundredth anniversary of the founding of the Colony of New Sweden in the State of Delaware, a number of distinguished Swedish scholars will be granted a leave of absence from their universities to lecture throughout the United States. In the field of experimental physics, Professor Karl Manne Georg Siegbahn, of the Swedish Academy of Science, has been selected. Further information regarding lecture arrangements may be obtained from The American Institute of Physics.

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¶ Dr. J. Neyman, reader in statistics at the University of London and docent at the University of Warsaw, delivered a series of lectures in Washington, D. C. April 5th to 12th through the sponsorship of the Graduate School of the Department of Agriculture. The subjects of Dr. Neyman's lectures included applications of mathematics and physics to the solution of problems in probability, which in turn are applicable to some of the problems in bacteriology, plant breeding and curve fitting that are under investigation in the Department of Agriculture. About 400 attended these lectures and participated in conferences.

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¶ Mr. W. L. Rast, who is a candidate for the Ph.D. degree in physics at The Pennsylvania State College in June, has accepted a position as research physicist for the Hamilton Watch Company, of Lancaster, Pa.

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¶ Mr. Bernard H. Porter, physicist with the Acheson Colloids Corporation, and Mr. Raymond Szymanowitz, technical director of the same company, jointly prepared a paper entitled "Colloidal Graphite and Its Role in the Ceramic Industry" for the Ceramic Convention at the Hotel Waldorf-Astoria on March 23. The authors, in presenting the development of colloidal graphite from the early work of E. G. Acheson to its present use in industrial lubrication, reviewed historical data of general interest, described the physical properties of colloidal graphite suspensions, and related these characteristics to glass-working techniques.

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Rheology Leaflet

¶ A new publication of the Society of Rheology entitled *The Rheology Leaflet* has just appeared. The purpose of this leaflet is to provide a medium for publishing general news items of special interest to rheologists. The first issue contains 16 pages, very well printed by the off-set process. The editor of this journal, Professor Wheeler P. Davey, Pennsylvania State College, State College, Pa., will be glad to have any news items telling of the activities of rheologists, for publication in this leaflet. The responsibility of publishing the *Rheology Leaflet* has fallen almost entirely on the shoulders of the editor and the secretary, Mr. R. L. Peek, Jr. They are to be congratulated on their fine job.

¶ Dr. Allan Fulson Odell, chemical director of the E. I. du Pont de Nemours plant at Arlington, N. J., died on April 10 at his home in Essex Fells, N. J.

Dr. Odell was assistant professor at the Louisiana State University from 1909–13. For the last twenty years he has been with the du Pont interests. He was active in the development of new transparent resins and in other work in the field of plastics. He was a member of the Society of Rheology.

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Conference on Industrial Physics

¶ The University of Pittsburgh will hold a second conference on industrial physics, May 22 at 9:30 A.M., in the Lecture Room of the new Mellon Institute in Pittsburgh. Formal papers will be presented by the following:

1. L. L. NETTLETON, *Gulf Research and Development Company.* **A Gravitation Survey along the Lincoln Highway**
2. H. P. GREENWALD, *Supervising Engineer of the Bureau of Mines, Pittsburgh.* **Physics of Subsidence and Ground Movements in Coal Mines**
3. H. B. MELLER AND F. F. RUPERT, *Mellon Institute of Industrial Research.* **Physics of Air Hygiene**
4. C. F. HILL, *Westinghouse Research Laboratory.* **The Problems of Physics in the Application of Dielectrics as Insulators**
   Luncheon, Webster Hall Hotel—Speaker to be announced.
5. F. L. BISHOP, *University of Pittsburgh and the American Window Glass Company.* **Glass**
6. W. E. FORSYTHE, *General Electric Company, Nela Park.* **The Physicist and the Incandescent Lamp**
7. E. W. SAMSON, *Hammermill Paper Company.* **Physics in the Paper Industry**

Near the Lecture Room, space will be provided for those who wish to exhibit instruments. At some time during the day, for those who wish it, arrangements will be made for a tour of the building and inspection of the various exhibits, illustrative of research accomplishments, which were gathered for the exhibit accompanying the dedication of the new Mellon Institute building.

Anyone interested is cordially invited to attend. Further information may be obtained from Professor A. G. Worthing, University of Pittsburgh.

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Third Dearborn Council on Chemurgy

¶ A Third Dearborn Conference on Chemurgy has been called for May 25–27. Mr. Francis Garvan, president of the Farm Chemurgic Council, will preside at the sessions which will be held in both Dearborn and Detroit. This conference is open to the public.

Francis Garvan

The Farm Chemurgic Council, which has grown in two years into a national institution, has as its motto "To Advance the Industrial Use of American Farm Products Through Applied Science."

Chemurgy, a coined word, is defined as putting chemistry along with all the allied sciences to work in an effort to

increase agricultural markets by finding new industrial uses for farm products. The name was adopted by the Council shortly after the first Dearborn conference which was held at Dearborn, Michigan, in May of 1935. To this conference came 300 representatives of agriculture, industry and science. Their encouraging reports on the possibilities in using farm crops industrially resulted in the formation of the permanent Farm Chemurgic Council.

Since the inception of the plan for the first conference, the Council has enjoyed the leadership and guidance of Mr. Francis P. Garvan, president of the Chemical Foundation and also of the Council, and Mr. William W. Buffum, general manager and treasurer of the Chemical Foundation. These officers have been tireless in their efforts in behalf of the Chemurgic Council and its activities.

Other executive officers of the Council include: Mr. Wheeler McMillen, editor of *Country Home;* Mr. Howard E. Coffin, chairman of the board of Southeastern Cottons, Inc.; Dr. Roger Adams, of the University of Illinois; Mr. Carl B. Fritsche, managing director of the Council, and Dr. H. E. Barnard, director of research.

Following a year of preliminary work and intensive study, the second Dearborn conference was held in May of 1936. Attendance at the second conference exceeded 1000 and it became necessary to hold some of the major sessions at one of Detroit's large downtown hotels. One hundred thousand copies of the proceedings of this conference were printed and distributed.

During its second year the Chemurgic Council enlarged its program and activities, holding and cooperating with regional and state chemurgic conferences in practically every section of the country. As a result of these conferences, regional and state chemurgic councils have been formed in many areas. Included in these Councils are: California, Florida, Arkansas, Georgia, Mississippi, Louisiana, Utah, Kansas, the Northwest Region (Washington, Oregon, Idaho and Montana) and the Midwestern Region, which includes the nine middle western states.

The Council continued also, in cooperation with the Chemical Foundation, to stimulate research of all kinds through its meetings and publications. Other activities included research-demonstration work such as manufacturing alcohol for blending with gascline for motor fuel; improving kraft and newsprint paper from Southern Pines, sweet potato starch, research in hemp, plastics, soy beans, and other special crops.

In addition to the reports of the Dearborn headquarters, all regional and state councils will report and participate in the third Dearborn conference which has been called for May 25, 26 and 27. Mr. Garvan, as president of the Council, will preside. Sessions will be held in both Dearborn and Detroit. The conference is open to the public.

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Mellon Institute Dedication

¶ At the formal dedication of the new home of the Mellon Institute May 6 in Carnegie Music Hall, with Dr. Edward R. Weidlein presiding, addresses were given by three Nobel prize winners—Dr. Irving Langmuir (chemistry), Dr. H. C. Urey (physical chemistry), and Dr. W. P. Murphy (medicine). Brief addresses were given at this event by Andrew W. Mellon and Richard K. Mellon, representing the Founders.

The Trustees' dinner was held in the evening of the same day, among the speakers being Dr. Benjamin T. Brooks, Dr. Karl T. Compton, and Dr. F. C. Whitmore. A. V. Davis, chairman of the board of the Aluminum Company of America, was toastmaster. Trustees of the Institute comprise John G. Bowman, president, Dr. Weidlein, vice president, Henry A. Phillips, secretary-treasurer, Andrew W. Mellon, and Richard K. Mellon.

The third outstanding scientific event of the dedicatory ceremonies was the Symposium on Recent Progress in Science, scheduled for the morning of Friday, May 7, in Carnegie Music Hall. Speakers included Dr. G. O. Curme, Jr., Dr. F. B. Jewett, Sir Frederick Banting, and Dr. W. W. G. Maclachlan.

Visitors from many parts of the world attended the exercises indicating the high position which the institute has won in pure and applied research. Great interest was shown in the unusual character of the institute's new home, which clothes in classic beauty a modern workshop of science in which many features of construction and equipment have been the result of exhaustive experimental research.

The program for the dedication was as follows:

Thursday, May 6, 9 A.M., assembly of out-of-town guests at the Institute's new building; 10 A.M., preview of the building for former fellows, past and present research donors, and other guests; 12 M., luncheon for visiting scientists, Hotel Schenley, and luncheon sponsored by the Robert Kennedy Duncan Club for former fellows, University Club; 2 P.M., dedication exercises, Carnegie Music Hall; Trustees' dinner, 7:30 P.M., William Penn Hotel.

Friday, May 7, 10 A.M., Symposium on Recent Progress of Science, Carnegie Music Hall; 12:30 P.M., luncheon for visiting scientists, University Club; 2:30 P.M., special meeting of Robert Kennedy Duncan Club, Institute Auditorium, and inspection of the new building and special exhibits; 7 P.M., group dinners for visiting scientists.

The new building was open to the public Saturday, May 8, from 10 A.M. to 10 P.M., and Sunday, May 9, from 1 to 7 P.M.

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Features of 1937 A.S.T.M. Annual Meeting

¶ During the week of June 28–July 2, the 1937 (Fortieth) Annual Meeting of the American Society for Testing Materials will be held at the Waldorf-Astoria, New York City. Throughout the week there will also be in progress the Fourth Exhibit of Testing Apparatus and Related Equipment. This will be the second meeting which the A.S.T.M. has held in New York City, the previous one having been there in 1912 during an international congress on testing materials. It is a coincidence that the society's second meeting in New York City should be held 25 years after the first one.

In order to provide ample time for the presentation and discussion of the large number of papers and reports scheduled, upwards of twenty formal sessions are being developed. Some of these will be devoted entirely to symposiums comprising several groups of papers. Among the groups of papers are a symposium on significance of tests of

coal and coke, another on correlation of laboratory and service tests of paints, and one on consistency: critical discussion of present-day practice in consistency measurements. There will be an extensive series of papers on asphalt, and several on water and on cast iron.

In addition to the displays of commercial apparatus and supplies, a number of A.S.T.M. committees will sponsor exhibits of their work including several of the committees which have extensive corrosion test programs under way and Committee E-4 on Metallography which this year will feature a special display of photomicrographs, radiographs and x-ray photographs. In addition, Committee D-9 on Electrical Insulating Materials will sponsor an interesting display and an extensive exhibit is being planned by the joint A.S.M.E.-A.S.T.M. Committee on Effect of Temperature on the Properties of Metals. It is expected that several college and industrial research laboratories may display special equipment and apparatus developed for interesting test and research work.

Details of the meeting are being developed by a local committee on arrangements headed by Dr. M. F. Skinker, assistant director of research, Brooklyn Edison Co.

Round Table Discussion of the Physical Basis of Metallic Properties

¶ At the request of several engineering societies the American Institute of Physics is sponsoring a meeting to organize Round Table Discussions of the Physical Basis of Metallic Properties, Monday evening, June 28, at the Waldorf-Astoria Hotel in New York. Representatives of the American Society for Testing Materials, American Society for Metals and American Institute of Mining and Metallurgical Engineers are expected to take part. Anyone interested in this subject will be welcome at this meeting.

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¶ The eleventh annual series of Priestley lectures at The Pennsylvania State College were given this year by George H. A. Clowes. Dr. Clowes is research director of the Lilly Laboratories. The dates and titles of the lectures were as follows:

May 4— I. **Chemical Criteria for Existence of Life.**
May 5— II. **On the Chemical and Physical Aspects of Cell Permeability.**
May 6—III. **On the Structure and Function of Protoplasm.**
May 7— IV. **Molecular Structure and Biological Activity of Physiologically Important Substances.**

Some of the New Books

Magnetochemie. Wilhelm Klemm, Pp. 262, Figs. 99, Physik und Chemie in Einzeldarstellungen, Band I. Akademische Verlagsgesallschaft, Leipzig, 1936. Price RM 18.

This book is an introduction to the methods of applying magnetic measurements to chemical problems by a well-known worker in this field. Addressing the book primarily to chemists, the author takes care to develop the fundamental magnetic definitions and methods of measurement, and the theories of dia- para- and ferromagnetism on which the interpretation of magnetic measurements in the solution of chemical problems is based.

The first of the three general sections into which the volume is divided discusses the nature of the magnetic field, definitions, units, nomenclature, behavior of matter in magnetic fields, and methods of measurement with many critical hints as to the limitations and possible errors in each. The second part deals with magnetic moments and atomic theory, including a brief review of the work of Curie leading to the famous law bearing his name. Weiss' hypothesis of internal fields, the Curie-Weiss law and Langevin's theories of dia- and paramagnetism are discussed in a qualitative but very clear manner. Some seventy-five pages are devoted to discussion of the older quantum theory and the modification brought about by wave mechanics in the calculation of magnetic moments. The author also includes some previously unpublished observations which point to the inclusion (at low temperature) of dysprosium and erbium among the list of ferromagnetic materials. In the third section, the author discusses the application of magnetic measurements to the solution of chemical problems. He shows how magnetic measurements can be used to study the structure of molecules and complexes of both organic and inorganic substances, and makes an interesting comparison between the magnetic and refractometric methods of studying molecular structure. Some forty pages are devoted to the treatment of magnetic measurements as an aid in determining the crystal structure of organic and inorganic substances and in studying the structure of pure metals and alloys. Here is included some of the recent work on the relationship between magnetic properties and distribution of atoms among atomic sites in alloys.

The book is well written and deserves to be widely read by those desiring an introductory treatment of this field.

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Physical Chemistry. F. H. MacDougall. Pp. 721+ix, Figs. 97. Macmillan Company, New York, 1936. Price $4.00.

The author has followed, in the main, the traditional order of presentation. A notable exception is found in the relatively early discussion of atomic structure. This procedure has, in the opinion of the author, a twofold justification. In the first place, an acquaintance with present-day views of atomic structure is essential to an adequate understanding of numerous topics, for instance, the de-

pendence of certain properties on molecular constitution, the behavior of electrolytes, the development of electromotive forces at phase boundaries, etc. In the second place, the study of various fields of investigation which have contributed to our knowledge of atomic structure is so fascinating that the interest of the student should be greatly deepened.

Electrotechnische Berichte. Edited by FRANZ MOELLER. Julius Springer. Price (3 volumes per year) per volume RM 48.

This new abstracting journal promises quick and accurate abstracts of articles appearing both in Germany and elsewhere in the field of electrical engineering. The first issue is dated March 18, 1937.

Among our Authors

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Contributed Original Research

Study of Magnetic Losses at Low Flux Densities in 35 Permalloy Sheet

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(Received April 13, 1937)

Energy losses in ferromagnetic materials subject to alternating fields have long been considered as due solely to hysteresis and eddy currents. However, at the low flux densities encountered in certain communication apparatus, a further loss is observed which has been variously termed "residual," "magnetic viscosity," or "square law hysteresis." The search for an explanation of this loss has led to precise measurements of hysteresis loops with a vacuum ballistic galvanometer, and of a.c. losses with inductance bridges. From these results, it appears that that part of the a.c. effective resistance of a coil on a ferromagnetic core which is proportional to the coil current is strictly identified with the hysteresis loop area as measured by a ballistic galvanometer, or as indicated by harmonic generation in the coil. The hysteresis loop can now be constructed in detail as to size and skewness on the basis of a.c. bridge measurements. This conclusion was reached previously on a compressed iron powder core, and is now confirmed on an annealed laminated 35 permalloy core. Observed eddy current losses for this core exceed those calculated from classical theory by 20 percent. This excess is ascribed to the presence of low permeability surface layers on the sheet magnetic material. The a.c. residual loss per cycle (nominally independent of frequency, like hysteresis) is not observed by ballistic galvanometer measurements, although it indicates an energy loss some eight times the hysteresis loss for the smallest loop measured ($B_m = 1.3$ gauss). Analysis of the residual loss shows that it increases with frequency up to about 500 cycles, and remains constant at higher frequencies (to 10,000 cycles per second). Concurrently with the increase of residual loss, the permeability of the alloy is observed to decline with increasing frequency about 1 percent below the value predicted from eddy current shielding. This effect is most noticeable at frequencies below 1000 cycles.

THE search for an explanation of the excessive magnetic losses observed at low flux densities by alternating current bridge measurement as compared with theoretical indications based on direct current measurements has led to a more accurate review of both types of measurement.[1–3] The a.c. energy loss per cycle which has received most study is the "residual" or "viscosity" loss.[4] It appears related to hysteresis loss because it is nominally independent of frequency, but it differs in being proportional to B_m^2 instead of B_m^3 which would be required by Rayleigh's law for hysteresis loops. Any satisfactory investigation of this anomalous loss demands precise determination of its value, and of its variation with frequency. For this purpose, ballistic galvanometer measurements of the hysteresis loop have been made and compared with bridge measurements of a well-annealed 35 permalloy laminated core.

In a previous paper, the magnetic properties of a ring of compressed powdered iron were studied at low flux densities using a sensitive vacuum galvanometer[3] and a multiple swing ballistic method.[1] Hysteresis loops were measured at flux densities B_m ranging from 1.8 to 115 gauss, which showed energy losses proportional to B_m^3 in accordance with Rayleigh's law. Alternating current measurements agreed with the ballistic measurements as to the magnitude of the energy loss and the proportionality to B_m^3, but in addition showed a residual loss proportional to B_m^2 which was of the same order of magnitude as the Rayleigh hysteresis at these low flux densities.

[1] W. B. Ellwood, Physics **6**, 215 (1935).
[2] V. E. Legg, Bell Sys. Tech. J. **15**, 39 (1936).
[3] W. B. Ellwood, Rev. Sci. Inst. **5**, 301 (1934).
[4] H. Jordan, E. N. T. **1**, 7 (1924); H. Wittke, Ann. d. Physik **23**, 442 (1935); F. Preisach, Zeits. f. Physik **94**, 277 (1935); R. Goldschmidt, Zeits. f. tech. Physik **13**, 534 (1932).

TABLE I.

Material	Initial permeability	$\lambda \times 10^4$	$c \times 10^6$	$a \times 10^6$	e/a	$B_r^* \times 10^4$
Compressed powder cores						
Grade B iron	35	7.0	110	50.	2.2	13.
81 permalloy	75	1.8	40	5.5	7.3	3.1
Laminated cores						
35 permalloy, annealed	1660	30.	60	5.0	12.	62.
38 permalloy, hard	100	7.0	118	9.6	12.	7.2
38 permalloy 800°, annealed	1330	9.0	27	1.5	18.	15.
40 permalloy 1000°, annealed	2060	12.0	20	1.4	14.	22.
45 permalloy, annealed	2550	5.4	14	.43	33.	8.2
78.5 permalloy, annealed	3900	8.1	0	0.6	0	18.
2.4–78 Cr permalloy, annealed	14600	6.4	3	.07	43.	7.6
8–79 Cr permalloy, annealed	3025	31.	14	2.6	5.4	60.
45–25 perminvar, annealed	450	0.02	0.0	.002	—	0.0

* These values of remanence were computed from Rayleigh's law as $3a\mu_0 B_m^2/16$ for $B_m = 2$.

The analysis of measurements made on the compressed dust core was complicated by the inhomogeneous structure, by the variety of particle shapes and thickness of insulation, and by the mechanical stresses incident to forming the core. To eliminate these objections, the present study was undertaken using a core consisting of well-annealed sheet material, for which eddy current losses can be calculated by classical formulae. Again, the ballistic tests described here show only Rayleigh type hysteresis losses, while the a.c. measurements show residual and eddy current losses in addition. The residual loss coefficient hitherto believed constant[5] over a wide frequency range is shown to decrease toward zero as the frequency approaches zero. The eddy current loss also exceeds that calculated by classical theory, and the observed inductance declines with increasing frequency at a rate beyond that due to eddy current shielding.

SELECTION OF MATERIAL

Considerable a.c. data were at hand from which to select material for this experiment. The properties of a few representative materials are given in Table I. The constants are defined by the equation

$$R_f/\mu_m f L_f = aB_m + ef + c = 8\pi W/B_m^2, \qquad (1)$$

where R_f is the difference between the resistances measured with a.c. and with d.c. on a toroidal coil with inductance of L_f due to core material of permeability μ_m, when the maximum flux density is $\pm B_m$ and the frequency is f cycles per second. Here the hysteresis coefficient is a, the eddy current coefficient e, and the residual loss term is c. W is the energy loss per cycle in ergs/cm^3 of core material. The permeability coefficient $\lambda = (\mu_m - \mu_0)/\mu_0 B_m$.

Table I shows that annealed 35 permalloy in sheet form has the most convenient values of B_r and c/a for further study of this effect. This alloy is of the face-centered cubic lattice type common to a large class of magnetic alloys.

The measurement of magnetic losses of 35 permalloy involved further refinements in technique. The high initial permeability required the construction of a special air core mutual inductance to simplify the measuring circuit and increase its stability. The high rate of change of permeability with temperature made it necessary to enclose both the specimen and the air core mutual inductance in a constant temperature box (at 37.1±0.01°C) throughout the tests.

THE SPECIMEN

The material was melted in a high frequency furnace, cast, and cold rolled with intermediate annealings, to strip of thickness $t = 0.0160$ cm and width 7.62 cm. Analysis showed the following composition: Ni, 35.00 percent; Fe, 64.25 percent; Mn, 0.40 percent; S, 0.030 percent; Si, 0.02 percent; C, 0.01 percent. The resistivity ρ was 82.2 micro-ohm-cm at 37.1°C. The strip was wound into a tight spiral core with successive turns insulated from each other by painting

[5] R. Gans and H. Wittke, Ann. d. Physik **23**, 459 (1935).

with a suspension of fine quartz powder in CCl_4 immediately prior to winding. The core had an effective magnetic diameter $d = 11.22$ cm, and cross-sectional area of alloy $A = 3.96$ cm^2. It was annealed in pure hydrogen for one hour at a temperature of 1000°C.

In order to protect the annealed core from mechanical stress during subsequent winding, it was placed on felt in an annular Bakelite box which held it without constraint. The box was wound with a 20-turn magnetizing coil using a flat tape composed of 28 parallel strands of insulated wires connected together at the ends. This winding practically covered the box with a single layer of wire, and gave a uniform magnetizing force. It was employed as the magnetizing coil in both the ballistic and the a.c. bridge measurements. For the ballistic tests, a layer of insulation was applied over the primary winding before applying the secondary winding. This insulation consisted of two wrappings of silk tape interspersed with a tinfoil sheath which formed a grounded electrostatic shield between the secondary and the primary winding. The foil was cut to avoid a short-circuited turn. The toroidal secondary winding consisted of 5000 turns No. 19 silk covered enamelled copper wire.

D.C. Apparatus

In the former experiment,[1] the specimen was compared with a fixed air core mutual inductance in terms of the galvanometer deflection and the primary currents required to obtain approximate balance. For this experiment, the circuit was modified so that the same current flowed in the primaries of both the specimen and the air core mutual (Fig. 1). Thus variable thermal effects in the primary circuits were eliminated and the measuring technique simplified. This required that the mutual inductance be adjustable so as to bring the unbalance onto the galvanometer scale.

The mutual inductance (approximately 0.260 henrys) was constructed for convenience in four separate sections. Each section had a hard wood toroidal core, a low resistance toroidal secondary winding, an inter-winding shield, and sectionalized primary windings on the outside. The secondary windings were connected in series with the galvanometer by a twisted shielded pair of wires. The primary winding groups were also connected in series, and adjusted so that the combination resulted in a mutual inductance of the right value to obtain balance. To eliminate humidity as a source of error each coil was painted with cellulose acetate, covered with silk tape, painted again, baked 48 hours at 108°C and finally potted in Superla wax in an earthenware jar with only the tops of the terminals exposed. All connections were made by soldering.

During the measurements, the maximum primary current corresponding to H_m was held constant to 0.01 percent by comparing the voltage drop across R_s with a battery of Weston standard cells. Switching was automatically performed by a photo-cell and selector switch mechanism previously described[3, 1] but not shown here. These operated switches S and S_1 at the proper time and in the right order. The difference in flux turns between the air core mutual inductance and the specimen was determined in terms of the ultimate galvanometer deflection as before. From this the difference in B between the side of the hysteresis loop and a straight line drawn through its tips could be computed for a given H. A number of values of this difference ΔB were thus determined for different values of H, and plotted to give the hysteresis loop.

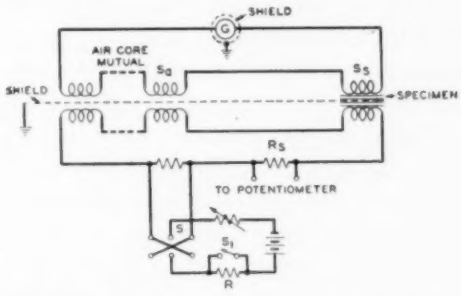

FIG. 1. Ballistic galvanometer circuit, showing adjustable air-core mutual inductance in series opposition with the test coil.

A.C. Apparatus

In order to compare results obtained by the vacuum ballistic galvanometer with those obtained with alternating currents, bridge measurements of resistance and inductance were made over the same range of flux densities a number of

frequencies ranging from 55 to 10,000~. The secondary winding was removed and the special 20-turn primary winding used for most of the

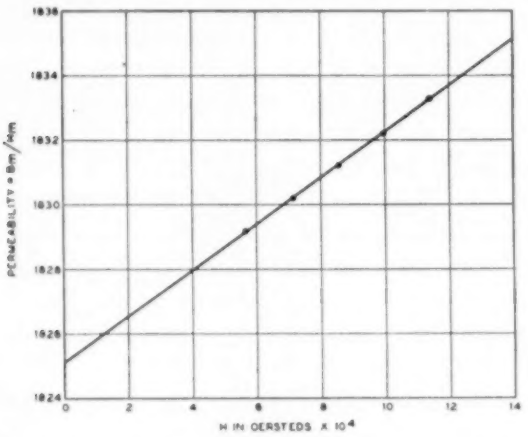

FIG. 2. Core permeability as measured by the ballistic galvanometer.

measurements. Later an additional 60-turn winding was used for checking the measurements in the low frequency range. In either case the inductance was low enough to depress any effect of distributed capacitance far below the precision of the measurements.

Measurements were made on a 10 ohm equal ratio arm inductance comparison bridge,[2] and were verified at low frequencies using a 1-ohm ratio arm bridge. Calibration of the bridge and standard coils was effected by making measurements over the entire frequency range on a calibrated high quality air core coil substituted for the test coil. The maximum correction required on this account was approximately 0.1 percent of the resistance due to the magnetic core.

The source of alternating current was an oscillator-amplifier supplying approximately 0.4 watt undistorted power, calibrated for these measurements against the Laboratories' standard frequency. The current was adjusted by the insertion of resistance in series with the primary of the bridge input transformer, and was measured by means of a thermocouple between the transformer secondary and the bridge.

The bridge unbalance was amplified by means of an impedance coupled amplifier for the 10-ohm bridge, and by means of a resistance coupled amplifier for the 1-ohm bridge. The amplified unbalance was observed by means of head phones at frequencies above 200 cycles, and by means of a vibration galvanometer at lower frequencies. The d.c. balance required bridge current of about 3 ma in the test coil winding, and had the same precision as the a.c. balance, *viz.*, ± 0.0002 ohm. The inductance readings were corrected for the air space within the winding, and had a relative accuracy of about 0.03 percent, and an absolute accuracy of approximately 0.1 percent.

D.C. RESULTS

The permeability $\mu = B_m/H_m$ of the specimen is shown as a function of H_m in Fig. 2, on a greatly enlarged scale in which the zero of permeability is not shown. The slope of this line gives $\lambda = 21.5 \times 10^{-4}$.

Values of ΔB are plotted against H for two different hysteresis loops in Fig. 3, from the area of which the energy loss W is computed. For comparison, Rayleigh loops are shown as broken lines. By analysis of the interior angles ϕ_+ and ϕ_- between the ΔB *vs.* H curve and the H axis at points $+H$ and $-H$, respectively, it is found that ϕ_+ is larger than for the Rayleigh loop, and is given by the relation $\tan \phi_+ = \mu_0 \lambda B_m$, while ϕ_- is a corresponding amount smaller than for the Rayleigh loop. The hysteresis coefficient a and the permeability coefficient, λ are related by the equation $a = 8\lambda/3\mu$ for a loop having para-

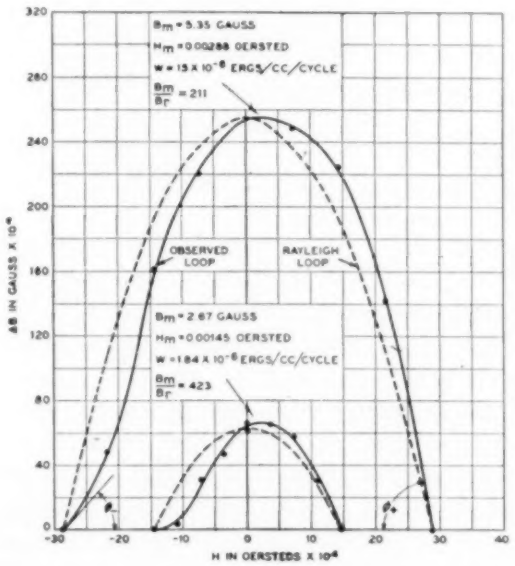
Bm = 5.35 GAUSS
Hm = 0.00288 OERSTED
W = 15 X 10⁻⁶ ERGS/CC/CYCLE
Bm/Br = 211
OBSERVED LOOP
RAYLEIGH LOOP
Bm = 2.67 GAUSS
Hm = 0.00145 OERSTED
W = 1.84 X 10⁻⁶ ERGS/CC/CYCLE
Bm/Br = 423
ΔB IN GAUSS X 10⁴
H IN OERSTEDS X 10⁴

FIG. 3. Two hysteresis (half) loops plotted with reference to a straight line through their tips.

bolic shape, in which case the interior angles are equal, and tan $\phi_{\pm}=\mu_0\lambda B_m$. Since the latter equation applies for ϕ_+ only on the observed skewed loop, it follows that the Rayleigh relation between a and λ is more or less inaccurate. In fact, the ratio of $8\lambda/3\mu$ to a is a measure of the skewness of the loop. For the present material, this ratio is about 1.15. This result is in accord with our previous data, but was evidently not noted by Rayleigh because the free poles in his magnetic circuit tended to mask the asymmetry. The fact that these hysteresis loops are slightly skewed shows that those processes which produce the familiar S shaped loop at high flux densities are already present at these low flux densities.

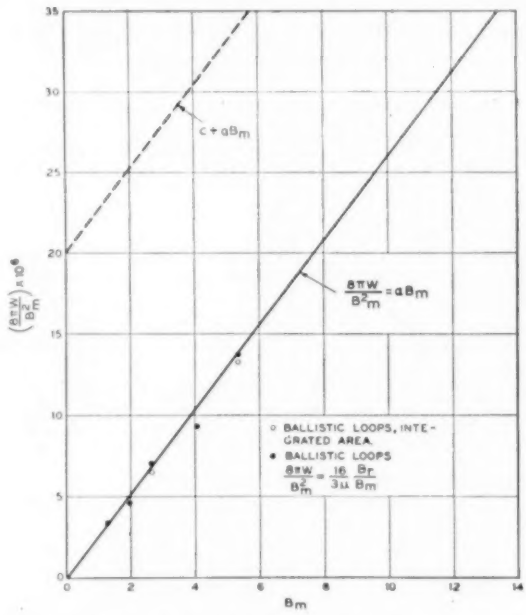

FIG. 4. Comparison of ballistic galvanometer and a.c. determinations of hysteresis loss. Note absence of residual loss from ballistic observations.

Despite a skewed shape, the area of the observed loop approximates closely the area of a parabola drawn through the remanence and the tips. Hence, supplementary values of energy loss W were obtained from remanence observations at several values of H_m, using the formula $W=2B_rH_m/3\pi$. The slenderness factor of the loops may be measured by the ratio B_m/B_r, which varies from 211 to 890 for the different loops studied.

The a.c. resistance introduced by the hysteresis loss of the core material yields the ratio $8\pi W/B_m^2$, as noted in Eq. (1). Values of this quantity computed from the areas of the loops of Fig. 3, and from remanence determinations are plotted in Fig. 4. They agree closely with the aB_m term of Eq. (1) obtained by a.c. measurements, as shown by the solid line in Fig. 4. The sum of $c+aB_m$ is shown by the broken line. It is evident that the ballistic galvanometer gives no indication of residual loss.

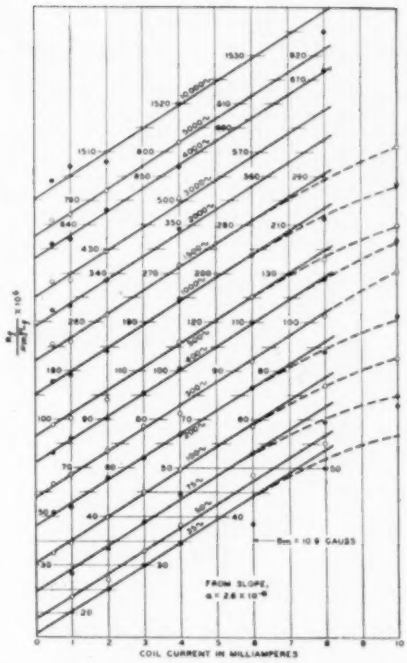

FIG. 5. a.c. bridge values of $R_f/\mu_m f L_f$ *vs.* coil current. Slope of the straight parallel lines gives the hysteresis coefficient a.

It is interesting to note that the hysteresis loop at low flux densities can now be constructed in detail using the data obtained from a.c. measurements. The remanence is $B_r=(3/16)a\mu_0B_m^2$ and tan $\phi_+=\mu_0\lambda B_m$. The angle included between the upper and lower branches of the loop at the tips is $(\phi_++\phi_-)$ and is given by the equation tan $[(1/2)(\phi_++\phi_-)]=(3/8)\mu_0^2aB_m$.

A.C. RESULTS

Values of R_f and L_f were measured as a function of the current at fixed frequencies. The values of $R_f/\mu_m f L_f$ are plotted in Fig. 5 as a function of current with frequency as a parameter. In order to shorten the vertical scale, the appropriate ordinates are indicated in connec-

TABLE II.

f	I_1 ma	E_3 mv	$a\times10^6$	f	I_1 ma	E_3 mv	$a\times10^6$
1000	2.0	0.0168	2.2	100	3.0	0.00447	2.6
	5.0	.133	2.8		5.0	.0106	2.2
	10.0	.55	2.9		10.0	.0473	2.5
					16.8	.1497	2.8
400	1.41	.00335	2.2				
	2.0	.00709	2.3	75	8.0	.0199	2.2
	3.0	.0158	2.3		10.0	.0335	2.3
	5.0	.0457	2.4		18.2	.112	2.4
	10.0	.195	2.5				
				50	10.0	.0359	3.7

tion with each line. These form a family of straight lines parallel to one another. This shows that the hysteresis coefficient is practically a constant over the low flux density range for all frequencies. From the slope of these straight lines the hysteresis coefficient a of Eq. (1) was calculated to be 2.6×10^{-6} which agrees with the value 2.53×10^{-6} computed from the ballistic tests. The divergence of the data from linearity at higher currents is shown by the dotted curves, which indicate divergence of the hysteresis loop from the Rayleigh form at higher flux densities.

Further information on hysteresis loss is obtained from measurements of harmonic voltages generated in the coil winding when there is current I_1 of frequency f. It has been shown[6] that the third harmonic voltage for materials with Rayleigh hysteresis loops is

$$E_3=0.6aB_m\mu_m L_m f I_1,$$

from which the hysteresis coefficient is

$$a=(25E_3/3fI_1^2)(Ad\times10^{-9}/2\mu_m{}^3L_m{}^3)^{\frac{1}{2}}.$$

Measurements of third harmonic voltages have been made on the coil described in this paper by P. A. Reiling and the results are shown in Table II. The values of a thus obtained show no consistent variation with current or frequency. They give an average value of 2.5×10^{-6}, which is in close agreement with the ballistic and a.c. bridge results. It therefore appears that that part of the effective resistance which is proportional to current is identifiable with hysteresis loss as obtained by ballistic means, and with that which generates harmonic voltages.

[6] E. Peterson, Bell Syst. Tech. J. **7**, 762 (1928).

The intercepts for $I=0$ in Fig. 5 are therefore due to eddy current and any residual losses. They have been plotted against frequency in Fig. 6. The line through these points is generally assumed to be straight, and the eddy current and residual loss coefficients are derived from its slope and intercept. It appears, however, that this line is not strictly straight, but has a somewhat steeper slope at lower frequencies, so that the ordinary graphical method of loss separation fails.

An analytical separation of losses can be made for any frequency interval by returning to the values of $R_f/\mu_0 f L_f$ as obtained from Fig. 5, subtracting the value of f_1 from that of f_2 and dividing by the frequency interval f_2-f_1 to give the eddy current coefficient e of Eq. (1).[7] Fig. 6

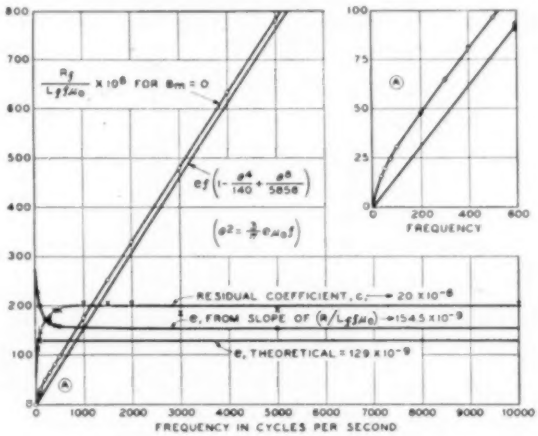
$\frac{R_f}{L_f f \mu_0}\times10^6$ FOR $\delta_m=0$
$ef\left(1-\frac{\sigma^4}{140}+\frac{\sigma^6}{5856}\right)$
$\left(\sigma^2=\frac{1}{2}\sigma_m\mu_0 f\right)$
RESIDUAL COEFFICIENT, c, → 20 X 10⁻⁶
e, FROM SLOPE OF $\left(R/L_f f\mu_0\right)$ → 154.5 X 10⁻⁹
e, THEORETICAL = 129 X 10⁻⁹
FREQUENCY IN CYCLES PER SECOND
FREQUENCY

FIG. 6. Intercepts of Fig. 5 *vs.* frequency. Slope of the curve gives eddy current coefficient e. Residual loss coefficient c varies with frequency near $f=0$.

gives e thus derived as a function of f, showing a value approximately 20 percent higher than calculated from the relation $e=4\pi^3t^2/3\rho$ at frequencies above 500~, and progressively higher as the frequency approaches zero.

The fact that e is larger than predictable from classical theory has been ascribed to the presence of a low permeability surface skin on practically all materials which have been reduced to sheet or wire form by mechanical deformation.[8] But since the eddy current coefficient depends only on the resistivity and effective thickness of the

[7] Correction terms must be included at higher frequencies to take account of eddy current shielding as noted in reference 2.

[8] E. Peterson and L. R. Wrathall, Proc. I. R. E. **24**, 275 (1936).

material, any apparent variation of e with frequency can only be interpreted as an indication that the residual loss is varying with frequency.

Taking the value of $e=154.5\times10^{-9}$ characteristic of the higher frequencies, the eddy current loss per cycle has been calculated, and is indicated in Fig. 6. The amount by which the observed loss exceeds the calculated eddy current loss gives the residual loss coefficient c. Thus, the value of c is found to be a constant 20×10^{-6} at frequencies above 500~, but to decline toward zero as the frequency approaches zero, in evident accord with the ballistic galvanometer result.

The inductance due to the core shows a similar frequency effect. The observed inductances for the 20 turn winding are given in Fig. 7. The values at each frequency for the various currents fall on a straight line, the slope of which gives the permeability coefficient, $\lambda=19.6\times10^{-4}$, for the lower frequencies where eddy current shielding can be neglected.

The values of L for $I=0$, obtained from Fig. 7 are plotted against frequency in Fig. 8. The most remarkable feature of this curve is the decline of inductance (or apparent permeability) of about 1 percent at low frequencies, where no

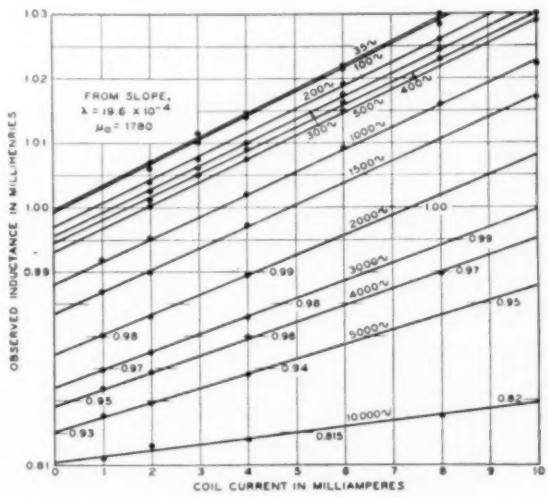

FIG. 7. Inductance observed on 20-turn coil, at various frequencies.

decrease on account of eddy current shielding is to be expected. The characteristic shielding curve has been computed using the value of e obtained

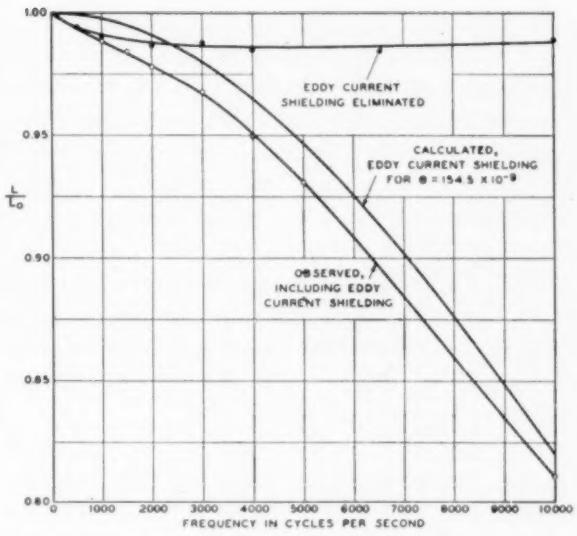
EDDY CURRENT SHIELDING ELIMINATED
CALCULATED, EDDY CURRENT SHIELDING FOR e = 154.5 x 10⁻⁹
OBSERVED, INCLUDING EDDY CURRENT SHIELDING
L/L₀
FREQUENCY IN CYCLES PER SECOND

FIG. 8. L/L_0 from intercepts of Fig. 7. Observed values about 1 percent lower than calculated for eddy current shielding.

from the resistance measurements in the relation

$$\frac{L}{L_0}=\frac{1}{\theta}\frac{\sinh\theta+\sin\theta}{\cosh\theta+\cos\theta}=\left(1-\frac{\theta^4}{30}+\frac{\theta^8}{732}-\cdots\right),^{9}$$

where $\theta=(3e\mu_0 f/\pi)^{\frac{1}{2}}$. Using the values of L/L_0 thus computed, the effect of eddy current shielding was eliminated from the observed values. The results plotted in the upper curve in Fig. 8, show a rapid decline of inductance or apparent permeability with increasing frequency at low frequencies, and the flattening off to a fairly constant value at higher frequencies.

The initial permeability thus obtained (average of results from the 20-turn and 60-turn windings) is 1780. This is somewhat lower than the value found by the ballistic galvanometer. The difference is due to magnetic aging which was observed to decrease the permeability of the core at the rate of approximately 1 percent per month. In contrast, no change of resistivity was detected in an accelerated aging test consisting of a bake at 100°C for 150 hours.

DISCUSSION

The ballistic data on both the present annealed 35 permalloy sheet core and the previous compressed powdered iron core show that the area of the hysteresis loop varies as B_m^3 in agree-

[9] The series is inaccurate at frequencies above 5000~.

ment with Rayleigh's law. The magnitude of the loss is not given by the fractional slope λ of the μ, B line as required by Rayleigh's law because the loops are not parabolic in shape. This discrepancy gives a measure of the skewness of the hysteresis loop. The B_m^3 portion of the a.c. data agrees with the loop areas obtained with the ballistic galvanometer. The threefold agreement between the ballistic data, the harmonic measurements, and the a.c. resistance measurements indicates that the hysteresis loop is substantially unchanged in shape over a frequency range extending from 0 to 10,000~.

Since the size and shape of the hysteresis loop are independent of frequency and the area is strictly proportional to B_m^3, it accounts for that part of the effective resistance of a coil on a ferromagnetic core which is porportional to the alternating magnetizing current. The remainder consists of eddy current and residual losses.

The ordinary graphical method of separating these losses is excluded by the obviously nonlinear relation between $R_f/L_f f\mu_0$ and f. Using an analytical method, the eddy current loss is found to be some 20 percent larger than computed by classical theory, indicating the presence of low permeability surface layers on the sheet material. The residual loss coefficient is found to increase with frequency up to about 500~, and to remain constant at higher frequencies (up to 10,000~).

The observed inductance diminishes with increasing frequency about 1 percent below the value calculated for eddy current shielding, the most noticeable decrease occurring below 1000~ where eddy current shielding is practically absent.

Various theories have been advanced to account for residual loss, as noted in a previous paper.[1] Goldschmidt[10] and Dannatt[11] have attributed the loss to nonhomogeneous alloy structure, or preferred axes in such directions as to give a flux component perpendicular to the sheet surface, with accompanying eddy-current losses unconstrained by the sheet thickness. This theory fails to account for residual losses in compressed powder cores, where eddy-currents are confined to single particles and cannot be increased by a modified direction of magnetic flux.

The most notable feature of residual loss is its large value for unannealed materials, and its extremely small values for well-annealed alloys, particularly 78.5 permalloy and 45–25 perminvar. (See Table I.) The permeability is increased by annealing while both c and a are decreased. On the other hand B_r is slightly increased. The decreases in hysteresis and residual loss are attributed to the decrease in work done against internal strains, which also tend to limit initial permeability.[12]

This suggests that residual loss may be due to elastic hysteresis or even simple mechanical friction, with magnetostriction providing the necessary coupling between the elastic or frictional variables and the magnetizing field, as pointed out in our previous paper.[1] Thus, in addition to losses from eddy-currents and magnetic hysteresis, mechanical work is done by the alternately expanding and contracting core—work expended on itself and its supports and insulation. Since the ballistic galvanometer measures only equilibrium values of B and H, this work is not revealed in the area of the ballistic loop. However, in the a.c. loop the magnetostriction strains produce stresses too rapidly to be relieved, so that B lags behind H with an absorption of energy into the surroundings. This results in an additional effective resistance beyond that due to magnetic hysteresis and eddy-currents. For a sufficiently slow process in well annealed material supported with minimum constraint, the stresses may relieve themselves by thermal agitation and do very little work. But for sufficiently rapid traversals of the loop, all the magnetrostrictive stresses will do the same amount of work on the core and its surroundings every cycle. Unannealed materials, or materials rigidly constrained, should continue to show residual loss at very low frequencies. The magnitude of c and its variation with frequency thus should depend on the magnetostrictive constant for the material, and on the types of dissipative constraints.

[10] R. Goldschmidt, Helv. Phys. Acta. **9**, 33 (1936).
[11] C. Dannatt, J. I. E. E. **79**, 667 (1936).
[12] R. M. Bozorth, Elec. Eng. **54**, 1251 (1935).

Heat Effects in Capillary Flow at High Rates of Shear*

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This paper describes a theoretical and experimental study of heat effects in viscous liquids up to rates of shear of the order of a million reciprocal seconds, corresponding to the rates experienced in lubrication practice. Even at much lower rates the effect of heat generated by viscous resistance in a capillary tube is sufficient to produce an appreciable drop in the apparent viscosity. This drop cannot be fully corrected for by laboratory observations of the mean efflux temperature, since the temperature rise will not be uniform over the cross section. Detailed calculations are necessary in order to distinguish between heat effects and non-Newtonian behavior. The theory is illustrated by experimental data on lubricating oils.

Introduction

We begin with a dimensional analysis of the problem as formulated in a previous paper,[1] where solutions were given for the limiting case of thermal equilibrium and the ideal case of *complete* adiabatic flow. The present paper is chiefly concerned with *incomplete* adiabatic flow.

Let it be required to determine, first, the general form of the equation for the temperature rise T at any radial distance x from the axis of a capillary tube of infinite length, in which a liquid of constant viscosity Z and thermal conductivity k is flowing under thermal equilibrium conditions. Let r denote the radius of the capillary and G the pressure gradient, or ratio of pressure drop P to the length L. Then T is some function of G, r, Z, k, and x. Here are six quantities requiring for their measurement four fundamental units. Hence from Buckingham's theorem[2, 3] there will be $6-4$ or 2 independent dimensionless products, one of which may be written TZk/G^2r^4 and the other x/r. Let x/r be represented by X; then the general form of the equation for temperature rise in this case must be

$$T=(G^2r^4/Zk)f_1(X). \qquad (1)$$

The specific form of the function f_1 cannot be predicted by dimensional analysis, but was shown by Eq. (10) of the previous paper to be $(1-X^4)/64$.

Under adiabatic conditions T cannot be influenced by thermal conductivity but will depend on the heat capacity per unit volume, h, and the time elapsed, t; so that T is some function of G, r, Z, h, x, and t. The relationship now involves 3 dimensionless products Th/Gr, Grt/Z, and X. These may be combined into 2 by expressing the requirement that T shall be directly proportional to t, hence

$$T=(G^2r^2t/hZ)f_2(X). \qquad (2)$$

A detailed solution similar to that underlying Eq. (6) of the other paper shows that in any case of adiabatic flow, complete or incomplete, $f_2(X)$ is equal to $X^2/4$. But it is only when the flow is *complete* that the time factor in Eq. (2) above can be replaced by y/v, where y is the distance from the inlet and v the velocity at a radius x. For practical applications, therefore, Eq. (2) above is preferable to Eq. (6) of the other paper.

The Drop in Apparent Viscosity

We have seen in the earlier paper how the drop in apparent viscosity with increasing rates of shear works out for the ideal case of thermal equilibrium. Proceeding to the more practical case of incomplete adiabatic flow, we first inquire to what extent the relations involved may be forecast by dimensional analysis. Let Y denote, as before, the apparent viscosity ratio Z_a/Z_1, where Z_1 is the viscosity at the wall temperature and Z_a the apparent viscosity com-

* Presented at the eighth annual meeting of the Society of Rheology, New York City, October 29–31, 1936.

[1] M. D. Hersey, "Note on Heat Effects in Capillary Flow," Physics **7**, 403–407 (1936).

[2] Edgar Buckingham, Phys. Rev. **4**, 345–376 (1914); Trans. A. S. M. E. **37**, 263–296 (1915).

[3] M. D. Hersey, *Theory of Lubrication* (Wiley, 1936).

puted in the conventional manner by applying Poiseuille's law[4] to the flow pressure observations. Then the percentage drop in apparent viscosity at any time is given by $100\ (1-Y)$ and it will be sufficient to investigate Y.

From physical considerations it is evident that Y may depend upon the pressure drop, the radius and length of the tube, the viscosity of the liquid and its heat capacity per unit volume, its temperature coefficient of viscosity, and the time elapsed since flow began. For the present application it is more convenient to describe conditions in terms of the apparent rate of shear at the wall, R_a, than in terms of the pressure drop; and since R_a is itself fixed by the pressure drop in conjunction with the remaining quantities mentioned, one variable is as good as the other for dimensional analysis. Neglecting the change in viscosity with pressure, and other still smaller effects, we may therefore write

$$Y=f(R_a, r, L, Z_1, h, a, t), \qquad (3)$$

in which a denotes the temperature coefficient, $(dZ/d\theta)/Z$, taken at the wall temperature $\theta=\theta_1$ corresponding to the viscosity $Z=Z_1$. It will be recalled that R_a is computed from the observed volumetric flow rate Q by the formula $4Q/\pi r^3$; and that R_a reduces to R_1, the true rate of shear at the wall, when the viscosity is uniform. Subsequent relations derived from Eq. (3) by dimensional analysis are equally valid if written with R_1 in place of R_a.

Going through the usual routine[2, 3] with Eq. (3) leads to the symbolic equation

$$F\left(Y, \frac{nR_a}{h}, R_a t, \frac{L}{r}\right)=0, \qquad (4)$$

which may or may not be solvable for Y in terms of the other three dimensionless variables explicitly. If the form of the function F turns out to be too complex for a direct solution, graphical or numerical methods may be required. In Eq. (4) the letter n has been introduced in place of $-aZ_1$. Keeping in mind our definition of the temperature coefficient a it will be evident that n is positive, and represents the negative of the viscosity-temperature slope, $dZ/d\theta$, at the wall temperature θ_1.

[4] For the derivation of Poiseuille's law and other elementary relations applicable to capillary flow see Chapter II of the *Theory of Lubrication* (reference 3).

Although the form of the function F is still unknown, various conclusions can immediately be drawn from Eq. (4). It shows, for example, that the same viscosity drop is to be expected under adiabatic conditions in any two experiments with geometrically similar capillary tubes provided the test conditions are so arranged that nR_a/h has the same numerical value in both experiments; and provided also that R_a is taken inversely proportional to the time elapsed. Any two liquids following Newton's law and having identical values for n/h would be expected to behave alike, regardless of their absolute viscosity or chemical constitution.

Although dimensional analysis cannot reveal the specific form of the function F, its general form as given in Eq. (4) has been confirmed by a detailed solution leading to the approximate result

$$Y\left(\frac{nR_a}{h}\right)\left[2\ln\left(Y\cdot R_a t\cdot\frac{r}{L}\right)-1\right]\frac{L}{r}-\frac{1}{Y}+1=0, \qquad (5)$$

in which ln refers to the natural logarithm. As a check it should be noted that when $n=0$ (flat viscosity-temperature curve) the heat effect disappears and Eq. (5) gives $Y=1$.

Incomplete Adiabatic Flow

The mathematical steps leading up to Eq. (5) are analogous to those outlined in the other paper[5] for the case of thermal equilibrium. The reader should, therefore, have no difficulty in reproducing the derivation if he is able to visualize clearly the concept of incomplete adiabatic flow.

This can best be done by drawing a parabolic envelope or wave front to represent the locus of all particles of the liquid at any time t which were starting off together from the inlet $(y=0)$ at the time $t=0$. It is assumed in the calculation that the vertex of this envelope has long since been discharged at the outlet $(y=L)$ so that the envelope is almost conical. The cross section of the envelope is identical with that of the capillary itself at the inlet, and remains so. At the outlet

[5] The notation of the two papers differs with regard to the symbols Z and X. In the present paper Z has been used for viscosity and X for the relative radius x/r.

end the circular cross section of the envelope is smaller than that of the capillary, but increases radially with time, coinciding with the wall of the capillary when $t=$ infinity.

Let the axis of the capillary be drawn in a horizontal position, with the liquid flowing toward the right. Let x' denote the radius of the envelope at any given distance y from the inlet. All particles of liquid either below or to the right of the envelope will be described as lying *outside*, and all particles above or to the left as lying *inside* of the envelope. Those particles lying inside the envelope follow the laws of complete adiabatic flow as expressed in the earlier paper, but those located outside have not had time to travel the entire distance y. If located now at some coordinate y, they were already part way along the tube at $t=0$. Eq. (2) with $f(X)=X^2/4$ is applicable both inside and outside the envelope provided t is defined as the time any given particle has been traveling within the capillary. Throughout the inside zone, t is equal to y/v but is less than the time elapsed since the flow began. This material had not entered the capillary at the time $t=0$. On the envelope, and in the outside zone, t is a constant to be interpreted as the total time since flow began and cannot be replaced by y/v. This interpretation is understood in the use of Eqs. (4) and (5).

To simplify the calculations leading to Eq. (5), stream-line motion without convective cross currents has been taken for granted; and it has been assumed that to a sufficient approximation, the pressure gradient G is equal to P/L at the mid-point $y=L/2$.

Experimental Results

Five experiments on three lubricating oils A, B, and C, are described below, using four capillaries I, II, III, and IV. These oils are all petroleum hydrocarbon products with viscosity ratings as indicated by Table I. Oil A is an S.A.E. 20 Pennsylvania oil, while B and C are, respectively, winter and summer grades of an improved motor oil[6] having a lower temperature coefficient of viscosity or higher *viscosity index*.[7] The capillaries are of glass having the dimensions given by Table II; outside diameter approximately 8 mm.

Table I. *Viscosity ratings.*

Oil	S. U. V. 100°F	S. U. V. 210°F	Centipoises 25°C (77°F)	Centipoises 98.9°C (210°F)	Temp. Coeff. Percent/deg. C at 25°C
A	349	55.8	135	7.43	−5.6
B	362	61.3	134	8.65	−4.1
C	939	102	378	16.9	−7.2

Table II. *Capillary dimensions.*

Cap. No.	Radius, r, cm	Length, L, cm	Ratio L/r
I	0.0109	3.52	322
II	.0257	3.78	147
III	.0427	3.69	86
IV	.024	5.26	219

Table III. *Flow pressure tests.*

Exp. No.	Oil Used	Bath Temp., θ_1, °F	Capillary No.	Maximum Range: Inlet Pressure P, lb./sq. in.	Maximum Range: Shearing Stress, F, dyne/sq.cm.	Maximum Range: Rate of Shear, R_a, seconds^{-1}
1	*A*	77	I	4550	$4.86(10)^5$	$1.49(10)^6$
2	*B*	"	"	4430	$4.84(10)^5$	$1.11(10)^6$
3	*C*	"	II	1110	$2.61(10)^5$	$1.04(10)^5$
4	"	86	III	127	$5.06(10)^4$	$2.17(10)^4$
5	"	210	IV	112	$1.73(10)^4$	$1.01(10)^5$

Flow pressure tests were conducted over the range of variables shown in Table III.

The inlet pressure readings were taken from a Bourdon gauge after an apparently steady condition of flow had been established, which might require from one to three minutes. Intermediate readings were taken at a succession of constant pressures up to the maximum noted in the table, for the purpose of determining whether or not the viscosity remained the same at all rates of flow. This is recognized as an important test in the development of lubricants in order to avoid materials that might introduce "false viscosity" or "non-Newtonian" behavior. The mean temperature rise at efflux was measured as carefully as possible with the aid of three thermocouples connected in series. The shearing stress F at the wall of the capillary was computed from the

[6] M. Otto, F. L. Miller, A. J. Blackwood, and G. H. B. Davis, "Improved Motor Oils," Proc. A. P. I. **15** (III), 76–89 (1934).

[7] For the definition and computation of the viscosity index see reference 8.

[8] E. W. Dean and G. H. B. Davis, Chem. Met. Eng. **36**, 618–619 (1929).

TABLE IV. *Viscosity drop at maximum rate of shear.*

Exp. No.	Initial Viscosity, Z_1, Centipoises	Observed Drop, Percent	Corrected Drop, Percent
1	135	81	36
2	134	67	22
3	378	39	19
4	270[a]	14	7
5	169	7	7

[a] Interpolated.

TABLE V. *Temperature rise at efflux.*

Exp. No.	P, lb./sq. in.	T_m, °F	
		Calc.	Obs.
1	4550	37.3	26.4
2	4430	36.3	33.2
3	1110	9.1	10.0
4	127	1.0	1.2
5	112	0.9	0.5

familiar expression $(r/L)P/2$ after first converting the inlet pressure P into dynes/sq. cm. The apparent rate of shear at the wall, R_a, was computed from the usual expression $(4/\pi)Q/r^3$ in which Q is the observed rate of efflux in volume units per unit time, and r the radius of the capillary.

Under the foregoing test conditions the observed viscosity drop due to the high rates of flow was greater than could be accounted for in the customary way on the basis of the thermocouple readings. In Table IV the total observed drop expressed as a percentage of the viscosity at low rates of shear is compared with the corrected drop, or amount remaining after correcting for the temperature rise on the assumption that it is uniformly distributed over the cross section. The initial viscosity is taken at the bath temperature and atmospheric pressure in accordance with Tables I and III. The fact that the observed drop is only reduced to about one-half by correcting for the mean efflux temperature gave ground for the suspicion of non-Newtonian behavior, and led to the present theoretical study.

The corresponding temperature rise at efflux as determined from thermocouple readings is recorded in the last column of Table V. These values had been used in computing the corrected drop in Table IV. In Table V are given also the theoretical values of the temperature rise T_m calculated from Eq. (1) of the previous paper for the mean temperature rise at efflux due to complete adiabatic flow. Not only are these calculated values of the right order of magnitude, but the observed values are much more nearly proportional to the inlet pressure than to the square of the inlet pressure which occurs in the thermal equilibrium formula, Eq. (13) of the previous paper. Hence it may be concluded that the experimental conditions are very much closer to the adiabatic state than to the thermal equilibrium condition.

The derivation of Tables IV and V will be more clearly understood after examining Table VI, in which the separate observations constituting Exp. No. 1 and No. 2 are reproduced. For example, the observed drop of 81 percent at the end point of Exp. No. 1, as recorded in Table IV, is found from Table VI by subtracting 26 from 135 centipoises, dividing by 135, and multiplying by 100. It is interesting to note the occurrence of a minimum point in the corrected apparent viscosities, both for Exp. No. 1 and No. 2. This suggests that at the higher values of the inlet pressure P the tendency for a decrease in viscosity due to heat effects is to some extent counterbalanced by the effect of pressure on viscosity (pp. 34–36 of reference 3).

TABLE VI. *Intermediate observations.*

Obs. No.	Inlet Pressure, P, lb./sq. in.	Rate of Shear, R_a, Seconds^{-1}	Efflux Temp. Obs., °F	Apparent Viscosity, Centipoises	
				Observed, F/R_a	Corrected to 77°F
Experiment No. 1, Oil *A*					
1	Low	Low	77.0	135	135
2	2660	$0.40(10)^6$	85.3	72	88
3	3260	$.60(10)^6$	89.1	58	83
4	3770	$.88(10)^6$	93.4	46	79
5	4270	$1.29(10)^6$	99.7	35	82
6	4550	$1.49(10)^6$	103.4	26	87
Experiment No. 2, Oil *B*					
1	Low	Low	77.0	134	134
2	2450	$0.34(10)^6$	90.0	77	101
3	3280	$.57(10)^6$	91.5	62	90
4	3970	$.90(10)^6$	101.0	47	92
5	4430	$1.11(10)^6$	110.2	44	105

Referring to Table IV we may continue the analysis from the adiabatic standpoint, and calculate the theoretical drop that would be expected if there is no departure from Newton's

TABLE VII. *Theoretical and observed viscosity drop.*

Exp. No.	Oil Used	Viscosity, Z_1, Centipoises	Slope, n, cp./deg. F	Viscosity Drop, Percent	
				Theoret.	Obs.
1	*A*	135	4.2	87	81
2	*B*	134	3.1	82	67
3	*C*	378	15.1[a]	64	39
4	"	270	9.8[a]	22	14
5	"	16.9	0.25[a]	11	7

[a] Interpolating between 77 and 210°F with the aid of Slotte's equation.

law. Under adiabatic conditions there is a maximum temperature rise at the wall and none along the axis. The amount of flow at a given mean temperature is therefore greater than would be computed from Poiseuille's law. If it is enough greater, the total observed drop in Table IV will be accounted for entirely by heat effects.

When the apparent viscosity ratio Y has been found by Eq. (5) the corresponding theoretical drop in viscosity due to heat effects is given by the value of $1-Y$. Applying Eq. (5) to the final run on oil *A*, Exp. No. 1, we have approximately, at 77°F, $n=0.042$ poise/deg. F; or, dividing by 69,000 to convert from poises into English units, $n=6.1\ (10)^{-7}$ lb. sec./sq. in./deg. F. Assuming roughly $h=136$ lb./sq. in./deg. F. (reference 3, page 100) we find that $n/h=4.49\ (10)^{-9}$ seconds. For the capillary in question, $L/r=322$. Taking arbitrarily $t=100$ seconds for the time of flow should be a sufficient approximation, since it can be shown that the difference in Y due to a change in t from 10 to 1000 seconds is only about 5 percent. Substituting these values we find from Eq. (5), at a rate of shear $R_a=1.49\ (10)^6$ reciprocal seconds, $Y=0.134$. Hence the theoretical adiabatic drop in apparent viscosity is $1-0.134$ or 87 percent for Exp. No. 1.

Proceeding in the same manner, Table VII has been compiled from the data corresponding to Exp. 1–5 inclusive.

Conclusion

It will at once be remarked that our heat effect explanation is a little too good. Whereas the conventional assumption of a uniform temperature over the cross section was insufficient to account for more than about half the observed drop in apparent viscosity, the adiabatic theory as applied in Table VII overshoots the mark and accounts for more than was observed.

The discrepancy is in part explained by the fact that the flow cannot, of course, be strictly adiabatic. This fact is evident from Table V. It may also be shown that a substantial part of the difference is due to the effect of high hydrostatic pressure acting to increase the viscosity of the oil near the inlet, and to a less extent all along the tube. It thus appears that the observed drop in viscosity can be accounted for by heat effects, without assuming that there would be any change in viscosity with rate of shear at constant temperature.

Note on the Filtering Action of Porous Media

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(Received March 12, 1937)

ONE of the problems in the science of rheology that is of interest in the production of petroleum is the filtering action of porous media for liquid suspensions. In the hydraulic rotary method of drilling oil wells[1] it is essential to circulate a colloidal suspension of some inert material past the exposed rock face in the hole, and further, in order to prevent fluid entry from the rock formations, it is often necessary to weight the fluid with suitable material so that the pressure in the hole is kept, with a reasonable factor of safety, always greater than the pressures prevailing in the various strata. Thus there is a tendency for the mud to pass into the porous rock but because the suspended particles find it difficult to enter the small pores

[1] A. G. Loomis, H. A. Ambrose and H. T. Kennedy, Physics **5**, 207 (1934).

a so-called "filter pack" rapidly forms which reduces further flow.

The question of the relative effectiveness of this filtering action is of importance to the petroleum engineer in controlling the drilling into oil formations. As no attempt at evaluating this effect other than estimates of the visual penetration[2] is apparent in the literature, an effort has been made to measure it by determining the permeabilities of rock cores before and after treatments with mud fluids under pressure. It is hoped that some of the results obtained in the early part of this study will be of general interest.

Apparatus and Procedure

A Berea sandstone of moderate permeability was selected for the experiments. Cylindrical cores one inch in diameter were mounted in the stainless steel core holder shown in Fig. 1, where AA and $A'A'$ are cylindrical rings in which the core is sealed with ordinary tar. These rings fit between end pieces in cylindrical grooves and when the large straight threads are tightened the core is held in position in a very tight seal. It has been found that the tar effectively compensates for small inequalities in the length of core and rings so that the seal is not broken when flow through the core is reversed. By using several rings it is possible to accommodate cores of various lengths. While no provision is made in the core holder of Fig. 1 for a pressure tap at the lower end of the core, it was found that the pressure drop through this end piece was negligible so that a standard pipe "T" afforded the necessary connection.

The technique followed in cutting and mounting these cores and in determining the permeabilities has been fully described elsewhere.[3] In accord with these former experiments no plugging action was observed when prefiltered deaerated distilled water was used for the permeability measurements.

The samples were mudded with a thixotropic water-mud (density 1.5 g/cc) which was made with commercial Baroid containing 5 percent bentonite by weight of total solids. One of the openings in the upper end of the core holder in Fig. 1 was connected to the mud reservoir so that the fluid could displace the water and fill the space before the core. The other opening was then connected through a small centrifugal pump back to the reservoir. This made it possible to study mudding with or without circulation. A mudding pressure of 80 lb./in.^{2} was maintained with a tank of compressed nitrogen and the mudding was continued for periods ranging from 2 to 30 hours.

As the fluid penetrated the saturated core an equal volume of water was forced from the low pressure end of the core holder and by noting this production of liquid as a function of time the penetration of the fluid into the core could be followed. After mudding, the filter pack was removed and the water permeability of the core was determined in the direction opposite to the mud penetration.

Theory

The formation of a filter pack may be considered analytically[4] as follows: It is obvious that the loss of solid fines to the rock is negligible compared to the loss of liquid if the layer at the interface soon becomes a reasonably effective filtering layer. Thus let a volume v of filter pack, with average liquid porosity $\bar{\rho}$, be formed by the penetration into the rock of Q volumes of liquid. Before separation there must have been $Q+v$ volume units of mud of original porosity ρ_0 so that:

$$Q+\bar{\rho}v=(Q+v)\rho_0 \quad \text{or} \quad Q/v=(\rho_0-\bar{\rho})/(1-\rho_0). \quad (1)$$

ρ_0 will be known from the composition of the mud and $\bar{\rho}$ may be determined, after any particular experiment, by measuring both Q and v or from the loss in weight on drying of a sample of the filter pack. Now the filter pack and core may be regarded as a series flow system through which water flows due to the mudding pressure. The input boundary of this system will vary with the flow according to Eq. (1) and the geometry of the region. Thus, in principle, it is possible to express the penetration Q or the volume of filter pack v as a function of time

[2] A. Knapp, Transactions, A. I. M. E. **69**, 1076 (1923).
[3] R. D. Wyckoff, H. G. Botset, M. Muskat and D. W. Reed, Rev. Sci. Inst. **4**, 394 (1933).
[4] The first analytical description of filtering action was made by D. R. Sperry, Met. and Chem. Eng. **15**, 198 (1916).

through the intermediate physical variable, the changing filter pack boundary, when D'Arcy's law[3] is assumed to hold for the flow through the filter pack and rock core. This is equivalent to neglecting short time pressure transients and it is obviously justifiable except for very short initial times. In particular, for a one-dimensional flow in the x direction into a uniform rock core of permeability k, length L and cross section area A, D'Arcy's law gives:

$$k=\frac{\mu L}{A}\frac{dQ/dt}{\Delta p_1} \quad \text{and} \quad \bar{k}=\frac{\mu x}{A}\frac{dQ/dt}{\Delta p_2}, \tag{2}$$

where μ is the viscosity of the liquid filtering through the system, $\bar{k}$ the average permeability of the filter pack of uniform thickness x, and Δp_1 and Δp_2 the pressure drops across the core and filter pack respectively. These equations

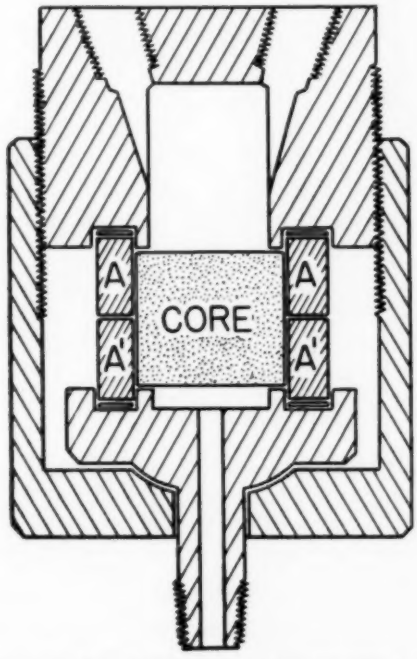

FIG. 1. Cross section of core holder showing core in position.

may be combined to express the rate of penetration into the core as:

$$\frac{dQ}{dt}=\frac{A\Delta p}{\mu}\Big/\left(\frac{L}{k}+\frac{Q}{\alpha A\bar{k}}\right), \tag{3}$$

where $\Delta p=\Delta p_1+\Delta p_2$, $\alpha=\rho_0-\bar{\rho}/1-\rho_0$ and $x=Q/\alpha A$ by Eq. (1). If the filter pack is assumed to be uniform in composition so that $\bar{\rho}$ and $\bar{k}$ are constants the differential Eq. (3) may be integrated to give:

$$Q^2+2Q\alpha A L\frac{k}{\bar{k}}=\frac{2\alpha A^2\bar{k}\Delta p}{\mu}t, \tag{4}$$

where $Q=0$ when $t=0$. The second term in this equation is equal to $2Q^2(\Delta p_1/\Delta p_2)$ from (2) and may be neglected for any filter packs which effectively reduce fluid entry into a porous rock. One has finally:

$$Q^2=(\alpha A x)^2=((2\alpha A^2\bar{k}\Delta p)/\mu)t. \tag{5}$$

EXPERIMENTAL RESULTS

Eq. (5) may be tested by plotting Q^2 against t. Fig. 2 shows the results of a typical mudding experiment without mud circulation and the straight line may be regarded as a verification of the assumption that the filter pack is of uniform composition and of the assumed mechanism of its formation. From the slope of this line the average permeability of the filter pack may be determined after the ratio α has been found from the liquid porosities. These values, $\bar{\rho}$ and ρ_0, were found to be around 40 percent and 83 percent, respectively, so that $\alpha=2.5$. Thus, in the experiment of Fig. 2, $\bar{k}$ was found to be 2.9×10^{-6} darcies.

An estimate of the average pore radius which is effective for the flow of a fluid through a porous medium may be made from the experimentally determined values of the permeability, k, and the porosity, ρ, as Traxler and Baum have done.[5] One considers a unit cube of the medium replaced by a number of capillary tubes of unit length and of radius r containing the same fluid volume and having the same fluid carrying capacity as the unit cube. With k in darcies one has:

$$r=2.81\times10^{-4}(k/\rho)^{\frac{1}{2}}. \tag{6}$$

For the filter packs of these experiments r is found to be of the order 10^{-6} cm which would indicate an average particle size of 10^{-5} cm if the particles were roughly spherical. However, there is considerable evidence[6] that the thixotropic properties of suspensions resulting from such stabilizing constituents as bentonite are due to the presence of flat particles with width

[5] R. N. Traxler and L. A. H. Baum, Physics **7**, 9 (1936).
[6] W. K. Lewis, Lombard Squires and W. I. Thompson, A. I. M. E. Transactions, **114**, 38 (1935); **118**, 71 (1936).

and length possibly one hundred times their thickness. Such particles might form very compact structures in mud filter packs through which the flow of water would be very difficult. Thus the extremely low permeabilities found for the filter packs in the present experiments are not unreasonable. It should be noted that the estimate of average particle size given above has little meaning (in the light of this picture) as Eq. (6) will give only effective values.

In the experiments with circulation of the mud the graph of Q^2 against t was initially a straight line but with a greater slope than the line in Fig. 2. This indicates that a less protective filter pack was built up under these conditions as it is unreasonable to expect the factor α to change enough to account for this increase. After a filter pack about 1 mm thick had formed it was found that Q^2 increased much faster than t until the circulation was decreased to a low rate. This was because the turbulent currents of mud tended to wash away the filter pack as it formed.

The permeabilities of cores were found to be about twice as large for gas flow as for the flow of water. For instance, these values for the core used in the experiments of Fig. 2 were 186 and 92.4 millidarcies, respectively. However, when carbon tetrachloride was used as the liquid and the core was sealed with a paste of litharge and glycerine, good agreement was obtained with the gas permeability showing that the lower water permeabilities were most probably due to a swelling of the bonding material of the sandstone. Since the water permeability of any one core was constant and reproducible it was considered a true property of the sandstone and consequently any decrease due to mudding could be used as a measure of the penetration of mud particles.

A similar difference between gas and liquid permeabilities recently has been reported[7] for the flow of furnace oil through cores of a much lower permeability (5 to 10 millidarcies). Such "tight" cores have not been studied extensively in connection with their interactions with liquids and consequently the interpretation of these results is somewhat obscure at present. In a study of the viscous flow in liquid films Bastow and Bowden[8] have shown that the flow of ordinary liquids through openings as small as 10^{-5} cm is of the same character, with the same coefficient of viscosity as for larger openings. In accordance with Eq. (6) this would indicate normal permeability behavior for cores with permeabilities at least as low as 1 millidarcy.

When water permeabilities were determined on mudded cores it was found that many small particles had filtered into the pore spaces and that they were distributed quite uniformly. Experiments on cores of various lengths indicated about the same relative permeability reductions and in one case the mudded face of a core 2.86 cm in length was sliced off, so that its new length was 2.55 cm, without changing the permeability appreciably. Traces of mud particles were observed in the liquid produced during the later stages of a mudding experiment showing positively that some particles could find their way through at least several centimeters of this rock. In all cases the total production was several times or more the pore volumes of the respective cores which probably accounts for this general distribution.

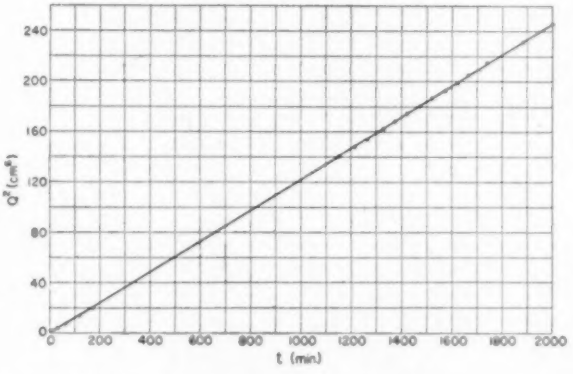

FIG. 2. Graph of liquid penetration squared *versus* time in mudding without circulation.

The water permeabilities after mudding were not simple unique properties of the cores but depended on the distribution of these solid particles in the pore spaces. This distribution was governed by the flow history after mudding. In general, flow caused the permeability to decrease because the particles tended to accumu-

[7] O. T. Koppius and W. G. Holton, paper presented at the meeting of American Physical Society, February 19, 1937.

[8] S. H. Bastow and F. P. Bowden, Proc. Roy. Soc. **A151**, 220 (1935).

late in the constrictions. When the pressure gradient was kept constant the permeability seemed to approach a steady value which was lower for lower gradients. A sharp increase in gradient always produced a sudden rise in permeability. Typical results of this type are shown in Fig. 3 where the permeability of a twice mudded core is plotted against flow for a section of its flow history.

It seems natural to think of the particles as forming bridges in the pore constrictions. These, then, might be expected to give way under a sufficient pressure difference and thus "open up" the core. With flow at a constant pressure gradient the permeability would be expected to approach a steady value when bridges had formed in most of the smaller constrictions.

The permeability to water was reduced by a single mudding to 50 or 60 percent of the original value but when the filter pack was kept from forming by removing it at intervals or by circulating the mud rapidly across the core face the reductions were much more than this. In one case the permeability was reduced to 4 percent of its original value in three successive muddings.

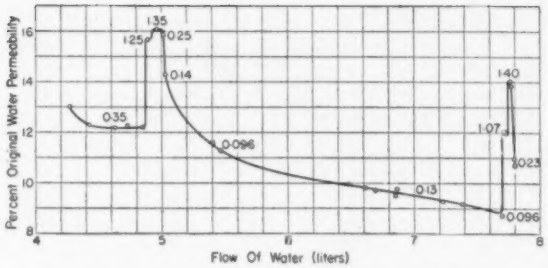

FIG. 3. Percent original water permeability of a twice mudded core *versus* flow. The pressure gradient across the core is indicated in atmospheres per cm by the figures. From 5 to 7.7 liters the decrease in gradient was gradual except for an increase to 0.18 atmospheres per cm at 5.5 liters.

The writer is indebted to Dr. Paul D. Foote, executive vice president of the Gulf Research & Development Company for permission to publish this paper and to Dr. Morris Muskat for many helpful criticisms.

The Effects of Pressure and Temperature on the Viscosity of Lubricating Oils

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The viscosities of three lubricating oils have been investigated at 100°, 130°, 210.2°F at pressures ranging from atmospheric to 4000 atmospheres (57,000 lb./in.²). While the oils were from fields widely separated geographically, their initial viscosities were matched at 0.4 poise at 130°F. At a pressure of 26,000 lb./in.² at 130°, however, the viscosities were strikingly different; the viscosity of the Pennsylvania oil increased 25-fold, and the Oklahoma oil 35-fold, but for the California sample the increase of viscosity was greater than 100-fold. The effect of pressure on the temperature coefficient of viscosity and the effect of temperature on the pressure coefficient of viscosity are discussed.

THE effect of pressure on the viscosity of fluid lubricants has been studied previously by several investigators. Experiments by Hersey[1] showed that the viscosity of oils increased considerably with moderate increase of pressure: further investigations by Hyde[2] at the National Physical Laboratory in England, Hersey and Shore,[3] and Kleinschmidt[4] in this country, increased our knowledge of the pressure effect of viscosity of oils of various kinds at several temperatures.

The increase of viscosity with pressure is a complicated phenomenon for even the so-called

[1] M. D. Hersey, J. Wash. Acad. Sci. **6**, 525 (1916).
[2] J. H. Hyde, Proc. Roy. Soc. **A97**, 240 (1920).
[3] M. D. Hersey and H. Shore, Mech. Eng. **50**, 221 (1928).
[4] R. V. Kleinschmidt, Trans. A. S. M. E. APM-50-4 (1928). Mech. Eng. **50**, 682 (1928).

simple liquids of high degree of purity, for it has been shown that viscosity is in general a strong function of molecular structure in liquids.[5, 6] Consequently, it would be expected that the viscosity of lubricating oils under high pressures would be so intricately related to composition that analyses of data taken on bulk oils would be unsatisfactory. Previous investigations[3, 4] have shown, however, that the pressure coefficient of viscosity of mineral oils is greater than that of fixed oils, but there is no existing information on the relation of the pressure coefficient to the basic composition of a hydrocarbon oil which has been refined by various methods. It would appear desirable, if further tests are to be made on refined oils, that more about the chemistry of the oils should be known, especially their chemical and physical properties as related to the basic crudes and methods of refining. The purpose of the present investigation is to make a start in this direction, to study the effect of pressure and temperature on three hydrocarbon oils that have been refined previously in a known manner and tested extensively as regards their physical and chemical properties.

The three oils used in this investigation were provided by Professor H. A. Everett of the department of mechanical engineering who had previously studied[7] many properties of them in conjunction with Dr. M. R. Fenske of the Petroleum Refining Laboratory of this school. The oils were from Pennsylvania, Oklahoma, and California crudes, blended with bright stock and neutrals to have the same viscosity of approximately 0.4 poise at 130°F.

In order to study the effects of pressure and temperature, the rolling-ball viscometer of Hersey and Shore[3] was adopted as the most suitable type for these experiments. The rest of the pressure apparatus was of design similar to that developed by Professor P. W. Bridgman of Harvard,[8] and used by the author in previous investigations.[6, 9, 10] Professor Bridgman kindly loaned diagrams and cooperated with the author in the building of the high pressure equipment of the physics department, and Mr. G. V. Luerssen of the Carpenter Steel Company contributed steel for the construction of apparatus. This investigation was made possible by the interest and cooperation of the Pennsylvania Grade Crude Oil Association which generously contributed funds. The experimental observations were made by the writer in the high pressure laboratory of the department of physics.

[5] P. W. Bridgman, Proc. Am. Acad. **61**, 57 (1926).
[6] R. B. Dow, Physics **6**, 71 (1935).
[7] H. A. Everett and F. C. Stewart, Penn. State College Bull. Eng. Exp. Station **44** (1935).
[8] P. W. Bridgman, *Physics of High Pressure* (Macmillan, 1931), Chap. II.
[9] R. B. Dow, J. Wash. Acad. Sci. **24**, 516 (1934).

Experimental Details

The rolling-ball viscometer and the auxiliary pressure apparatus are shown in Fig. 1. The viscometer was rotated through a known, small angle (10°) from its horizontal position by tilting the apparatus about an axis which was supported by an iron frame work. A handle attached to the upper part of the viscometer frame allowed the viscometer to be tilted by hand in either direction. In the viscometer, of dimensions used by Hersey and Shore,[3] a $\frac{1}{4}''$ ball bearing rolled down the bottom wall of an axial hole, 10 inches in length and 27/64 inches in diameter, when the viscometer was inclined to the horizontal. In order to measure the viscosity of a liquid in this apparatus, it is necessary to know the time required for the ball to traverse the length of the inclined path. To measure the roll time insulated electrical contacts with external connections were fitted into two steel plugs which were screwed into both ends of the viscometer to make it pressure tight. Both the plugs and washers were of conventional design used in high pressure investigations. It will be noted that when the ball reaches either end of its path, the relay circuit is completed through the viscometer and oil film to the ball which touches the insulated contact. The time of roll can be recorded by any of several means; in these measurements a calibrated stopwatch operated by hand was found convenient for the purpose. The arrival of the ball at one of the contacts was signalled by a simple vacuum tube relay device.

The viscometer with its supporting frame was surrounded by a thermostated water bath which two stirrers kept in constant circulation. The

[10] R. B. Dow and M. R. Fenske, Ind. Eng. Chem. **27**, 165 (1935).

thermostat circuit operated a vacuum tube relay to control a gas valve which supplied one or two Meker burners that heated the bath. A thermometer, calibrated against one certified by the National Bureau of Standards, reading to 1/10 degree was used in this investigation for temperature measurement. The recorded temperatures are accurate to within $\pm 0.02°C$.

Pressure was generated by a hand pump which can be safely operated to 20,000 lb./in.^{2} without undue effort. The pump connected directly to an intensifier which permitted about a fourfold increase of pressure. Before this pressure could be used in the viscometer, however, means had to be provided for separating the transmitting liquid from the test liquid, and for measuring the pressure, the gauge on the pump being inaccurate for precise measurements. A cylindrical steel chamber connected between the intensifier and viscometer served both purposes; a flexible copper sylphon provided mechanical separation of the liquids, and a coil of manganin wire mounted on a suitable plug allowed the pressure to be measured by observing the change of its electrical resistance with pressure by means of a Carey-Foster bridge. It is known that the change of electrical resistance of manganin with pressure is linear.[11] The gauge was made of No. 40 B & S double silk covered manganin wire obtained from Driver Harris Company. The resistance was about 120 ohms at atmospheric pressure. Dr. L. H. Adams of the Geophysical Laboratory provided the important service of calibrating the manganin coil against the standard in his laboratory. The calibration obtained by Dr. Adams was 2.335×10^{-6} cm^2/kg. Finally, a connecting pipe from the cylindrical chamber led to a connection at the top center of the viscometer, thus completing the system under pressure.

Method of Computation and Data

The absolute viscosities of the three oils are desired at the three chosen temperatures of 100°, 130°, and 210.2°F at various pressures within the experimental range. Since lubricating oils freeze at fairly low pressures at moderate temperatures, the pressure range was more restricted in the present case than is usual for most liquids. Consequently, the highest pressures used in this study are of the order of 55,000 lb./in.^{2}; in every case the highest pressure recorded is considerably

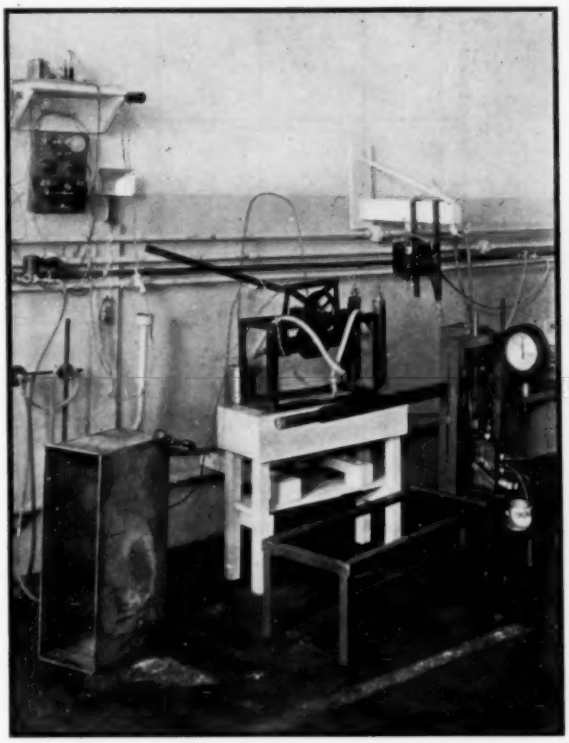

Fig. 1. Rolling-ball viscometer and auxiliary pressure apparatus.

below that where solidification begins. The beginning of solidification is noticed when the viscosity becomes abnormally great; when it is complete, the ball ceases to roll. The recorded data for a viscosity determination were then: the roll time in seconds, the thermometer reading in degrees Fahrenheit, and the pressure read on the Carey-Foster bridge in terms of length of slide wire. The roll time was taken as the average of roll times in both directions of tilt, and readings were recorded both for increasing and decreasing steps of pressure. When the roll time was less than 10 seconds, twenty or thirty observations were taken but as it increased, the number of observations was accordingly decreased. The corresponding pressures were obtained by multiplying the equivalent lengths of slide wire by the pressure coefficient of manganin, and converting the result to pounds per square inch.

The theory of the rolling-ball viscometer has been developed from a dimensional standpoint by

[11] P. W. Bridgman, *Physics of High Pressure* (Macmillan, 1931) p. 73.

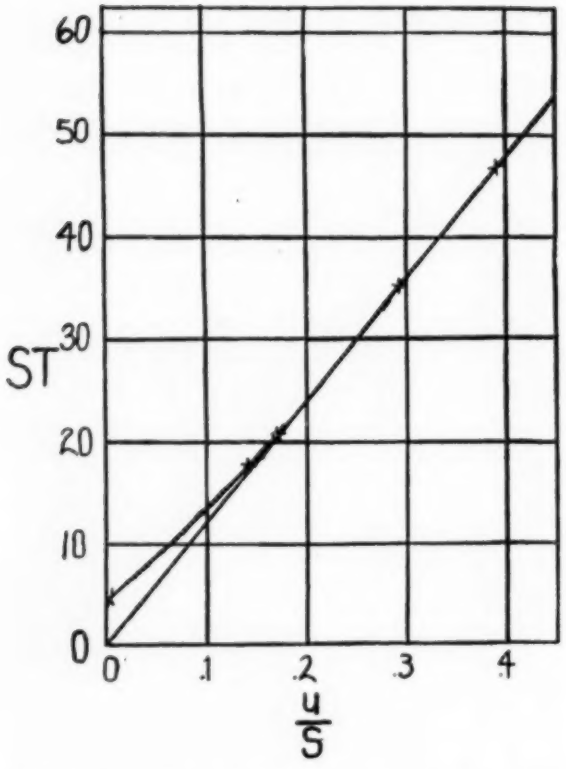

FIG. 2. Calibration curve of viscometer for 10° angle of tilt.

Hersey[1, 3] and his method was followed in computing the absolute viscosities in poises. Since the roll times as measured are only relative, the viscometer must be calibrated by observing the roll times with liquids of known viscosity. This involves plotting a function ST against the function U/S. T is the roll time, U the kinematic viscosity, and S is a function of density equal to $(\rho_0/\rho-1)^{\frac{1}{2}}$ when ρ_0 is the density of the steel of the ball and ρ is the density of the oils in grams per cubic centimeter. Fig. 2 shows the calibration curve for the viscometer, when the angle of tilt is about 10°.

Writing the relation $ST=f(U/S)$ (1)

the Eq. (1) becomes $ST=118(U/S)$ (2)

for long roll times. Solving (2) for the viscosity ($\mu=\rho U$)

$$\mu=((7.36-\rho)/118)T \tag{3}$$

on setting $T_1=118/(7.36-\rho)$ where T_1 represents the roll time in seconds for a viscosity of one poise

$$\mu=T/T_1. \tag{4}$$

Thus the computation of viscosity is done in one of two ways: if the roll time is short (region where the calibration curve departs from linearity) U of Eq. (1) is solved for by referring directly to the curve; if the roll time is long (region where ST varies linearly with U/S), Eq. (3) can be used directly to give μ. The values of ρ were obtained by interpolating the pressure-volume-temperature data of Dow;[9] since the change of volume of oils with pressure is not a strong function of compositon, it is sufficiently accurate to use the P-V-T data of Pennsylvania oil interpolated for 100°, 130°, and 210.2°F.

There are, however, various corrections to be made in applying the formulae. These have been discussed by Hersey. In the present case they reduce to two, namely the change in length of path due to pressure, and the initial acceleration of the ball. The first correction involves the change of length of the viscometer, change of diameter of the ball, and the change of position of the electrical contacts. The first two are negligible in these experiments but the effect of change of position of the contacts is appreciable. The correction was made by observing the change of length of the external stem of one of the end plugs of the viscometer for a certain pressure change. It was observed that at a pressure of 13,500 lb./in.^{2} the stem was displaced 0.025 inch, which amounts to a correction of 0.05 inch for both contacts. This negative correction was assumed to be linear with pressure. The second correction, that for the initial acceleration, was computed from Hersey's formula

$$\Delta T/T_0=0.21\{1-(1-8/KT_0^2)^{\frac{1}{2}}\}.$$

T_0 is the roll time and K is a constant equal to 8.3. This correction is also negative, amounting to 16.8 percent when the roll time is 1 sec. but vanishing if the roll time exceeds 10 seconds.

TABLE I. *Data for calibration of viscometer; the functions ST and U/S.*

LIQUID	ST	U/S
Kerosene	4.69	0.0055
Merusol	20.8	.173
Oil, S.A.E. 10	17.5	.143
" " 20	34.6	.293
" " 30	46.8	.390
" " 40	62.5	.467

Table I contains the data used to obtain the calibration curve of Fig. 2. Kerosene, a light mineral oil, and a series of four graded oils of viscosity S.A.E. No. 10, No. 20, No. 30, and No. 40, respectively, were used as calibrating liquids. The values of the kinematic viscosities of these liquids were directly determined at 100°F by Mr. C. E. Fink of our Petroleum Refining Laboratory. The author is indebted to him for carefully checking the viscosities in the standard viscometers of that laboratory. The density of the ball and the densities of the calibrating oils were determined in a conventional manner by weighing in specific gravity bottles.

Table II summarizes the data that were derived by computation. They were obtained graphically by plotting on a large scale the computed values of μ against pressure, drawing smooth curves through the plotted points, and then reading from the curves the values of μ corresponding to every one or two thousand units of pressure. The principal sources of error in these data are in the determination of the pressures and the roll times. The average inaccuracy of the former amounts to about 1 percent, while the latter, expressed in the unit of coefficient of viscosity, may be as high as 3 percent when the roll time is as low as 2 or 3 seconds. Another way of estimating the erratic error in the determinations is to consider the deviations of the computed values of μ from the curves that were

TABLE II. *Viscosity-pressure data.*

Pressure (lb./in.²)	Viscosity in Centipoises		
	Penn.	Okla.	Cal.
	100°F		
14.2	83	94	114
1000	91	119	146
2000	106	145	183
3000	123	175	225
4000	145	209	278
5000	169	247	346
6000	198	293	433
7000	232	344	533
8000	268	405	655
9000	310	475	811
10×10^3	357	557	995
12	485	775	1540
14	654	1060	2200
16	850	1430	
18	1100	1940	
20	1420		
22	1830		

TABLE II (*Continued*).

Pressure (lb./in.²)	Viscosity in Centipoises		
	Penn.	Okla.	Cal.
	130°F		
14.2	41	43	42
1000	51	54	57
2000	60	66	68
3000	64	75	80
4000	73	85	99
5000	82	95	124
6000	91	102	154
7000	100	118	190
8000	111	131	232
9000	124	149	281
10×10^3	143	170	340
12	191	231	490
14	249	318	692
16	315	428	960
18	408	564	1320
20	524	740	1830
22	663	940	2510
24	830	1170	3400
26	1030	1500	4540
28	1260	2030	
30	1560	2840	
32	1960		
34	2460		
	210.2°F		
14.2	7	10	13
1000	9	12	15
2000	10	14	17
3000	13	16	19
4000	15	18	21
5000	17	20	24
6000	19	22	25
7000	20	24	27
8000	22	27	30
9000	24	30	33
10×10^3	26	33	37
12	31	40	45
14	36	50	55
16	44	59	70
18	52	71	90
20	62	85	116
22	73	104	153
24	87	128	202
26	103	154	260
28	123	185	327
30	145	219	408
32	171	262	510
34	202	314	655
36	242	375	846
38	287	454	1080
40	337	549	1400
42	393	654	1790
44	457	770	2270
46	535	890	2890
48	627	1010	
50	732	1150	
52	846	1290	
54	973	1430	

drawn to smooth or average the results. In no case did the computed value of μ deviate by more than 1 percent from the value read from the curve which was drawn through the same pressure ordinate. In compiling the data of Table I, only three figures have been considered as significant.

Discussed Results

The data of Table II show significant differences for the viscosity of the three oils under pressure. Perhaps one of the most striking is the viscosities of the oils at 130°F at a pressure of 26,000 lb./in.^{2}; at atmospheric pressure the oils have a matched viscosity of 0.4 poise but at the higher pressure the change amounts to a 25-fold increase for the Pennsylvania sample, a 35-fold increase for the Oklahoma sample, and an increase greater than 100-fold for the California oil. Further inspection of Table II shows that, likewise, the data at 100° and 210.2°F indicate that the effect of pressure is the greatest on the viscosity of the California oil and the least for the Pennsylvania oil. Assuming that the California oil is of more complicated composition from the standpoint of viscosity, due to the probable greater number of ring compounds or cycloparaffins (C_nH_{2n}), it is not surprising that the effect of pressure is greatest for this sample. It has been previously mentioned that the viscosity of liquids under pressure is a strong function of composition and one must admit that the viscosity effects in these oils are exceedingly complicated due to the corresponding complication of chemical makeup or structure.

The second order effects are: that of pressure on the average temperature coefficient of viscosity, and that of temperature on the average pressure coefficient of viscosity. Considering the effect of pressure on the *temperature* coefficient of viscosity computed between 100° and 210.2°F, it has been found that for the Pennsylvania oil an increase of 20,000 lb./in.^{2} increases the coefficient by 5 percent, for the Oklahoma sample an increase of 18,000 lb./in.^{2} increases the coefficient by 7.8 percent, and in the case of the remaining oil, the increase amounts to 10 percent for a pressure difference of only 14,000 lb./in.^{2}. Now the effect of temperature on the *pressure* coefficient of viscosity, averaged over 10,000 lb./in.^{2}, is more noticeable although the changes occur in the same order; an increase of 110.2°F decreases the pressure coefficient by 18 percent for the Pennsylvania oil, 53 percent for the Oklahoma oil, and 76 percent for the California oil. Qualitatively, these oils show the same abnormality as pure liquids at high pressures in the relative change of viscosity with temperature,[5] most temperature effects being less at high pressures due to the constraining action of the high pressure on the normal thermal agitation in the liquid. These considerations show clearly that the influences of temperature and pressure on the first order effects of viscosity are correspondingly greater for the California oil than for the Pennsylvania oil.

In conclusion, it may be said that the changes of viscosity of these oils are remotely connected with the volume changes that occur in the pressure range of these experiments. For a pressure of 28,400 lb./in.^{2} at 210°F the change of volume of these oils is about 10 percent, as contrasted to a change of viscosity which may be as high as 80-fold. It has been shown[12] with the available data on volume and viscosity that Batschinski's relation, which states that viscosity is a function of volume alone, is not valid for fluid lubricants at high pressures. The data of this paper likewise show the invalidity of the relation when viscosity is found as a function of volume.

[12] R. B. Dow, Physics **6**, 270 (1935).

THE Summer Session of the University of Rochester, College of Arts and Science, announces two summer courses in photography to be given under the joint auspices of the Institute of Applied Optics of the University of Rochester and the Eastman Kodak Research Laboratory and under the immediate supervision of Dr. T. R. Wilkins and Dr. Walter Clark. These courses, concentrated each into three weeks, will be similar to those given in the regular curriculum of the Institute of Optics. The elementary course will run from June 22–July 13 and the advanced from July 5–23. The lectures in the advanced course will be given by C. E. K. Mees, L. A. Jones and W. Clark of the Kodak Research Laboratories. The courses overlap by a week in which topics common to both (such as the making of emulsions and color photography) will be covered. Registration may be for either one or both courses.

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July 5– 9 Photographic photometry and spectrophotometry. Brian O'Brien.

July 12–16 The photographic emulsion as a tool in atomic nuclear research. T. R. Wilkins.

Trips of inspection of the Kodak Park Laboratories and the Kodak Camera Works will be featured. A detailed announcement may be obtained by addressing the Institute of Applied Optics, or the director of the Summer Session of the University of Rochester.

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CURRENT LITERATURE OF PHYSICS

THE Editors present for convenient reference in this section a list of those articles dealing with physics published in some thirty selected journals. Their definition of the scope of physics and their selection of the particular journals to be included are necessarily based on their interpretation of the wishes of the majority of the readers. The emphasis is placed on prompt mention and convenience of use rather than completeness. For many other excellent articles and publications, reference should be made to the regular abstract journals. Miss Margaret Shields, Physics Librarian at Princeton University, very kindly prepared the listings for the foreign language journals.

American Physics Teacher

VOL. 5, NO. 2, APRIL, 1937.

Physical Content of Quantum Mechanics. pp. 49–55. ***W. V. Houston***

Criteria of Consistency and Concepts of the Dielectric Constant. pp. 56–61. ***A. G. Worthing***

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Photoelectric Determination of h as an Undergraduate Experiment. pp. 65–67. ***Winthrop R. Wright***

Early History of Graphs in Physical Literature. pp. 68–70. ***M. C. Shields***

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Eye as a Part of the Optical System of the Microscope and the Telescope. pp. 74–77. ***T. Townsend Smith***

Diffraction of Light, An Experimental Demonstration. pp. 78–80. ***F. A. Molby***

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Why the Woman Student Does Not Elect Physics. pp. 82–85. ***John B. Daffin***

Photography in the Physics Curriculum. pp. 85–86. ***Paul E. Boucher***

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Convenient Mercury-Vapor Lamp. p. 87. ***R. A. Ramsey***

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SERIES 5, VOL. 28, NO. 5, FEBRUARY 14, 1937.

Analysis of X-Ray Absorption into Photoabsorption and Compton Scattering. pp. 385–408.

K Transition for Elements from Aluminum to Tungsten. pp. 409–437. ***H. Rindfleisch***

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Classical Dynamics of the Electron. Theory of First Functions and Proper Moment of the Electron. pp. 560–562. ***B. Kwal***

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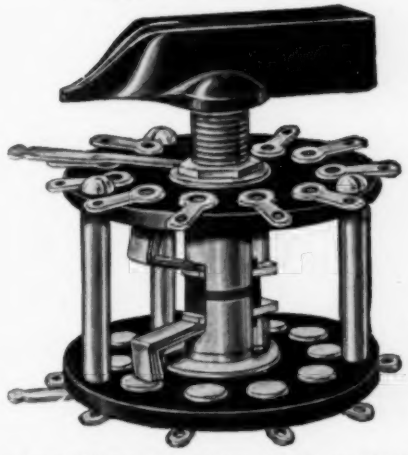

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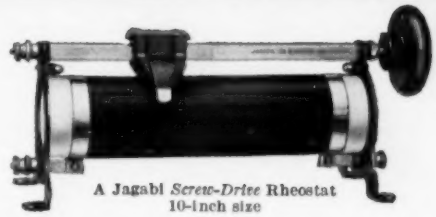

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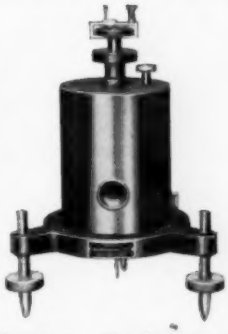

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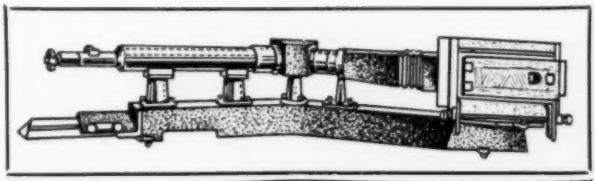

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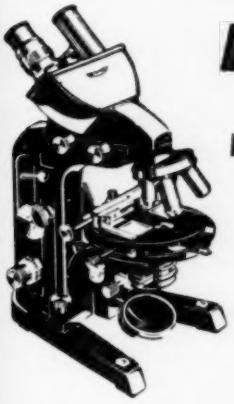

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